The potential of electricity generation with renewable energy sources in Finland 2030

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Abstract

Electricity systems are planned so the supply and demand always meet. However, since the demand undergoes hourly, daily and seasonal variations, the electricity supply must be very flexible in order to adapt to the constant changes. Recently, a growing climate- and environmental awareness has driven the energy sector in a more sustainable direction. This means that renewable energy sources are increasing in number and importance. However, renewable energy generation is non-dispatchable, which means it cannot be generated on demand and thus lacks the flexibility that electricity systems require. This means that the flexibility must be achieved in other ways. One method that has been proven in practice is energy storage solutions.

The subject of study in this thesis is the electricity system of Finland and the possibilities Finland has to commit to generation without fossil fuels before 2030. Two different cases were examined, one where Finland would rely completely on renewable electricity generation and one where electricity generation would be based on renewable energy sources and the three nuclear reactors in Olkiluoto, the already existing Olkiluoto 1 and 2 as well as Olkiluoto 3, which is nearing completion. All the calculations were based on data from 2018, which was scaled to match approximations for the situation in 2030. Existing studies and the current generation capacity were used as reference to approximate the generation potential of the different energy sources. A total renewable electricity generation potential of 89.5 TWh was identified, which means a 280% increase compared to the current generation would be possible.

Based on the assumptions made in the study, the Finnish energy ssytem cannot be 100% renewable and self-sufficient yet in 2030. The remaining demand was 6.7 TWh, which would have to be imported from abroad or generated with other means. When the existing nuclear capacity in Olkiluoto was included in the generation, the capacity was enough to cover the assumed demand. An optimisation of energy sources was conducted with the objective to minimise the required energy storage need. The optimisation ruled solar power as too variable to be feasible in a electricity system with limited energy storage capacity. At the same time, wind power, bioenergy and hydropower were concluded as important generation technologies, together with nuclear power.

The emission reduction potential in generation with renewable energy sources and nuclear power was also concluded as significant. Direct emissions in such a system would decrease to zero, while the life-cycle emissions would be reduced by 17% from the current level. However, since the generation was 28.7 TWh larger in the electricity system which was considered as self-sufficient, the emission intensity per generated TWh showed a reduction potential of 43%.

A carbon-free electricity system is in line with the targets of the European Union to become carbon neutral in 2050. Still, the electricity system is not on its own able to reduce the total emissions by 55% from the 1990 levels, which is a goal set up by the Finnish government. The calculations in the thesis were based on data from Finland, but the results can also be applied to other countries which are similar in climate and consumption habits. For instance, the rest of the Nordic countries.

Keywords: carbon-free electricity, electricity generation, energy storage, Finland, renewable energy

Abstrakt

Elsystem är planerade så att eltillförseln alltid anpassas till att stämma överens med elanvändningen. Elanvändningen genomgår dock förändringar på tim-, dags- och årstidsbasis, vilket resulterar i att eltillförseln måste vara flexibel, för att kunna anpassas i enlighet med användningen. Under senaste tid har en ökad klimat- och miljömedvetenhet drivit hela energisektorn mot en mera hållbar riktning, vilket betyder att förnybara energikällor har ökat i antal och betydelse. Det är dock värt att notera att förnybara energikällor är icke-reglerbara, det vill säga att elproduktionen inte kan styras i enlighet med elanvändningen och således saknar de den flexibilitet som elsystem kräver. Flexibiliteten måste därmed uppnås med andra medel. En metod som har bevisats fungera i praktiken är olika lösningar för energilagring.

I den här avhandlingen har elsystemet i Finland undersökts i enlighet med de möjligheter som Finland har att kunna frångå elproduktion med fossila bränslen före år 2030. Två olika fall har undersökts. I det första fallet undersöktes ifall Finland skulle kunna vara helt och hållet bunden till elproduktion med förnybara energikällor, medan det andra fallet studerade ett scenario där elproduktionen skulle utföras med förnybara energikällor och kärnkraft. I beräkningarna användes data från 2018, som sedan skalades om för att stämma överens med den approximerade efterfrågan för 2030. Befintlig forskning och de nuvarande produktionskapaciteterna användes som referens för att uppskatta den potentiella produktionskapaciteten för de olika energikällorna. Totalt sett kunde en potential på 89,5 TWh identifieras för de förnybara energikällorna, vilket skulle motsvara en ökning på 280 % jämfört med den nuvarande produktionen.

Baserat på de antaganden som gjordes inom ramen för detta arbete, skulle det finska elsystemet inte kunna vara både fullständigt förnybart och självförsörjande ännu år 2030. Enligt uträkningarna var det återstående elbehovet 6,7 TWh. Den resterande elmängden borde endera importeras från utlandet eller produceras på andra sätt. Däremot, när den existerande kärnkraftskapaciteten i Olkiluoto inberäknades i den totala produktionskapaciteten, räckte produktionskapaciteten till för att täcka den antagna konsumtionen. För det senare fallet utfördes även en optimering för att hitta den förmånligaste fördelningen av energiproduktionskapaciteten med hänsyn till att minimera det krav som systemet ställde på energilagringskapaciteten. I enlighet med optimeringen

kunde vindkraft, bioenergi och vattenkraft tillsammans med kärnkraft konstateras vara en viktig del av en fossilfri elproduktion. Samtidigt kunde solenergi identifieras vara för variabelt för att lämpa sig för ett elsystem där energilagringskapaciteten är begränsad.

Potentialen att minska utsläppen då elproduktionen sköts med förnybara energikällor och kärnkraft kunde även konstateras vara avsevärd. De direkta utsläppen skulle sjunka till noll, medan livscykelutsläppen skulle minska med 17% från den nuvarande nivån. Det måste dock påpekas att elproduktionen var 28,7 TWh högre i det självförsörjande, fossilfria elsystemet och därmed var utsläppsintensiteten per producerad TWh 43% mindre än i det nuvarande elsystemet.

Eftersom ett fossilfritt elsystem saknar direkta utsläpp, är det i enlighet med Europeiska Unionens mål att vara koldioxidneutral år 2050. Ett fossilfritt elsystem är dock inte ensamt tillräckligt för att minska utsläppen med 55% från utsläppsnivån år 1990, vilket är ett mål som den finska regeringen ställt upp. Fastän beräkningarna i avhandlingen är baserade på data från Finland, kan resultaten även tillämpas på andra länder med liknande klimat och konsumtionsvanor, exempelvis de andra nordiska länderna.

Sökord: elproduktion, energilagring, Finland, fossilfri el, förnybar energi

Abbreviations

Abbreviation	Definition
BEV	Battery electric vehicle
CAES	Compressed air energy storage
CES	Cryogenic energy storage
CHP	Combined heat and power
EV	Electric vehicle
FCV	Fuel cell vehicle
FIT	Feed-in tariff
GHG	Greenhouse gas
GWP	Global warming potential
ICEV	Internal combustion engine vehicle
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MEAE	Ministry of Economic Affairs and Employment
MOI	Moment of inertia
MTC	Ministry of Transport and Communications
ORC	Organic Rankine cycle
P2G	Power-to-gas
P2H	Power-to-hydrogen
PCM	Phase change materials
PEV	Plug-in electric vehicle
PHES	Pumped hydro energy storage

PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaic
PVGIS	Photovoltaic Global Information System
RES	Renewable energy source
SNG	Synthetic natural gas
STUK	Radiation and Nuclear Safety Authority
TES	Thermal energy storage
V2G	Vehicle-to-grid
VTT	Technical Research Centre of Finland

Entries

Symbol	Explanation	Unit
A	Area	m^2
E	Energy	Wh or J
I	Moment of inertia	kg m^2
P	Power	W
T	Temperature	K
U	Internal energy	kJ
$\dot{V}$	Volumetric flow	m^3/s
c_p	Specific heat capacity	kJ/(kg K)
h	Height	m
k	Shape factor	-
r	Radius	m
t	Time	h
v	Speed	m/s
η	Efficiency	-
ρ	Density	kg/m^3
ω	angular velocity	s^{-1}

The increment operator (Δ) before any symbol expresses change in the specific variable

Indexes 1 and 2 are for state at beginning and end respectively

Equations in the thesis are expressed with variables in specified units

Chemical substances

Substance	Abbreviation
Carbon dioxide	CO_2
Hydrogen	H_2
Lithium nitrate trihydrate	$LiNO_3 \cdot 3H_2O$
Methane	CH_4

Contents

1. Introduction

1.1. Background

The growth of the world population is incrementally decreasing (Worldometer, 2019), but according to the International Energy Agency (IEA) the energy demand of the world is rapidly increasing (IEA, 2019). Scholars argue that the increase in energy demand is due to the growing wealth of the world (Magazzino, 2016), but while the wealth and energy demand have increased, so have the emissions and pollutions too (Jackson et al., 2017; Tucker, 1995). This is because a major pollutant is the energy sector and a major part of the world energy production is still done with fossil fuels, i.e. by burning oil, gas and coal (IEA, 2019). However, there is a growing concern for the causes of the different emissions that originate from the combustion of fossil fuels. The reported causes vary from particulate emissions to increased atmospheric concentrations of greenhouse gasses (GHG), especially carbon dioxide (CO_2) (Watson, Rodhe, Oeschger & Siegenthaler, 1990). Possible outcomes are numerous, and the most discussed and disputed of the potential consequences is the intensification of the natural greenhouse effect which, in turn, causes an acceleration of the natural climate change (Stern & Kaufmann, 2014). Several studies show that an accelerated climate change would have far-reaching consequences for the whole world, from higher mean temperatures to expanded desert areas and melting polar ices, all of which threaten life on our planet as we know it (Houghton, Jenkins & Ephraums, 1990). Apart from the wildly discussed possible acceleration of the natural climate change, pollutions and emissions are an undisputable issue, that have an impact on our health and environment, regardless other possible consequences (Holdren & Smith, 2000).

In order to mitigate the causes of emissions and pollutions, the world has taken action. Different long- and short-term pollution limits and emission targets have been set by various organisations, both within the European Union and globally. Based on these climate agreements and emission targets, nations have been able to make their own decisions about how to apply them into their national agenda. The national governments can use a remuneration policy which encourages the use of renewable energy or a prohibiting policy which will force companies to cut down their emissions under threat of sanctions (Haas et al., 2004).

These actions have also forced the energy production to take a leap in a more sustainable direction with renewable energy sources (RES) as an alternative solution to the conventional solutions. However, RES have not been able to replace the vast use of fossil fuels in a bigger scale yet (IEA, 2019). The main reasons, to name a few, are the increased need to implement new technology to support the dispersed energy generation (Hammons, 2008) and the non-dispatchable nature of RES which results in an additional need for flexibility to meet the requirements the energy demand sets on the generation side (Lund, Lindgren, Mikkola & Salpakari, 2015). This means the change to renewable energy is not completely without problems and, thus, all energy cannot be changed to renewable without further technology development and changes in the current energy system. A widely used solution to add flexibility to the energy systems with considerable amounts of RES are energy storage solutions (Lund et al., 2015).

1.2. Aim and methods

The non-dispatchability of RES has left a need for energy storage solutions. Nevertheless, energy storage technologies are still very inefficient and expensive, which consequentially raises the price of renewable energy integration and usage (Lund et al., 2015). In order to make the transition from the current energy system towards an energy system that relies fully on renewable energy, the cost of the renewable energy system would preferably be minimised. Since the energy storage solutions are so valuable, the whole system could benefit from a well thought out blend of different RES that complement each other, thus, lowering the overall storage need.

The energy system can be divided into several sectors: electricity, heating and transport. All three sectors are subject to extensive changes in order to meet the growing demands of the future. Due to an increased number of household appliances that require electricity and the electrification of the transportation sector in the future, the electricity sector is expected to grow in the coming years (Koljonen, Similä, Sipilä, Helynen & Airaksinen, 2012). Further, the power and heat generation have the biggest emissions of all three sectors (IEA, 2019). On these grounds, this thesis will focus solely on the generation of electric energy. In other words, the thesis will examine different aspects in the RES and energy storage solutions when used in electricity generation.

The thesis will be limited to studying the case of Finland. Finland is a highly developed country in the northern hemisphere that has four seasons, which introduces the seasonal variations into the equation. When studying Finland, the research results can also be utilised in other countries with a similar climate. In terms of electricity, Finland is not currently self-sufficient and, therefore, must import some energy from neighbouring countries, namely Sweden, Norway and Russia (Statistics Finland, 2019; IEA, 2018). In the current system, almost half of the electricity demand is met with RES, about a third is produced with nuclear power and the remaining sixth is fulfilled with fossil fuels (Statistics Finland, 2019). The Finnish government has included the climate as a main point in the government programme 2019–2023 (Finnish Government, 2019). The programme states clearly that it is in line with the long-term goal of the EU to become carbon neutral by 2050. The programme also states that Finland already achieved the strict EU version of the short-term goal in the Kyoto Protocol, to reduce the emissions by 20% compared to 1990 levels before 2030. However, this does not seem to be enough. The government programme states that now Finland is "tightening the emissions reduction obligation for 2030 to at least 55 per cent below the 1990 emissions level" (Finnish Government, 2019, p. 33).

This thesis will delve into two cases, one where all electricity generation is based on RES and another where also the existing nuclear power capacity is taken into consideration. Both cases focus on the electricity system in Finland in 2030. A system based on renewables or renewables and nuclear power is considered as carbon neutral, which is in line with the long-term goal of the EU for 2050, the so called "Green Deal" (European Commission, 2019b). For the two cases the emission reductions will be examined. This is done to see if a modernisation of this kind in the electricity system would be enough to achieve an overall reduction of 55% in the emission levels compared to numbers from 1990, a main goal in the Finnish government programme (Finnish Government, 2019), as mentioned earlier. The possibilities that Finland has to further grow the renewable electricity generation will also be presented.

In order to establish the possibilities of the use of renewable energy in Finland, the potential upper limit of renewable electricity generation and energy storage need will be calculated, while the lower limits are dictated by the already existing renewable energy generation capacity. Since the seasonal variations result in an uneven availability of the renewable energy as well as a fluctuating electricity demand, an optimisation to solve for the most feasible distribution of electricity generation, while minimising the energy storage need, will be realised. The future is difficult to foretell, so the present state of technology is used as the standard in the calculations.

1.3. Disposition

This thesis consists of six more chapters. In chapter two, the relevant theory is presented and some general subject definitions are given as support for the rest of the dissertation. The third chapter concentrates on placing the theory from chapter two into the Finnish perspective. The current state of the energy system and especially the renewable electricity production in Finland are presented. The future aspects of electricity generation in Finland are examined in chapter four, when the chapter addresses the estimated electricity demand of 2030, the maximum potential of RES in electricity generation and the possibilities for storage solutions. Chapter five focuses on the optimal utilisation of the increased RES potential. The chapter examines two cases, an all renewable case and a case where the existing nuclear power is also accounted for. An optimisation is realised in order to find the most beneficial energy distribution among the RES while minimising the energy storage capacity required. The sixth chapter will focus on the analysis of the calculations and optimisation done in the fifth chapter. Both the limitations and possibilities will be examined, building up with arguments for the discussion and summary in the last chapter. The thesis is ended in chapter seven with discussion about the usability of the cost-model, possibilities to achieve the suggested generation mix and to what extent the results can be generalised to other countries. The last chapter will also summarise the research and give suggestions for possible future subjects to resolve in the area of study.

2. Theory

2.1. Electricity

Energy follows the law of conservation. This means energy cannot be created nor destroyed, just transformed into different forms. One of the most commercially used forms of energy is electric energy, or more commonly electricity. Electric energy is driven by an electric current and an electric potential difference, which are connected and delivered by an electric circuit. Since energy cannot be created, the process of developing electricity is commonly referred to as electricity generation. Electricity is generally generated by an electromechanical generator. The generator has a magnetic field which is rotated next to conducting materials. The electricity generation is accomplished by forcing a turbine, which is connected to the generator axis, into rotation. When the magnetic field changes, a current is induced in the conductor according to Faraday's law, thus converting mechanical energy to electric energy (Breeze, 2015). Electricity is generated in different kinds of power plants. There are generally three kinds of power plants, the ones that use fossil fuels, nuclear power plants and power plants that are powered by RES. In most of these, electricity generation is based on the same principles. Either, the fuel is consumed in order to generate heat, which is then used to vaporise water and the steam that is generated is then fed through a turbine. This kind of electricity generation follows the Rankine cycle, an ideal thermodynamic cycle which describes how heat is converted into mechanical work, while water, which acts as a working fluid, undergoes a phase change (Woodruff & Lammers, 1935). Alternatively, the kinetic or potential energy present in the energy source can be directly utilised to rotate the turbine and output electricity. This is the case in wind power and hydropower generation. Other methods of electricity generation are photovoltaics (PV) and geothermal energy.

For this thesis it is worth noting that electricity is only a part of the energy system. Apart from electrical power, the energy system also involves the energy and fuels used for heating and in the transport sector. However, this thesis will only focus on the generation and consumption of electricity.

2.2. Electrical grid

The electrical grid is a network that connects consumers and suppliers in terms of electricity. All electrical grids consist of at least a power source, substations and power lines of two types, high voltage transmission lines and low voltage distribution lines. The power source is usually a power plant of some kind and located near the point of supply of the fuel and away from crowded areas. For this reason, the electricity might be required at a far distance from the source. Thus, the substations and powerlines are needed. In the substations, the electrical voltage is increased for the transmission lines and decreased for the distribution lines that reach the consumer. A higher voltage is needed for the transportation of the electricity in order to minimise the losses due to resistance in the transmission cables. The voltage is then lowered for the distribution lines, since consumer applications are not built for the high voltage. Both the high voltage transmission cables and the distribution lines are responsible for the actual transportation of the electricity (Fingrid, 2019a). The main objective of the electrical grid is to provide consumers with an uninterrupted, reliable and stable supply of energy at a high quality (Child & Breyer, 2016b).

The electricity supply is defined as the total amount of electrical energy available for use at a given time. The demand, or load, is the total amount of electricity which is removed from the grid by consumers at that same given time. In electrical energy systems these two must continuously match, i.e. the supply needs to meet the demand at all times. Normally, this is handled with a set of different kinds of power plants, which complement each other in terms of response time. In this way, the power plants can collectively satisfy the requirements that the varying demand puts on the supply side (Lund et al., 2015).

The electricity demand varies over time and the supply needs to meet the demand in order to achieve a balanced energy system. The electricity supply may be bigger than the demand, but it is not preferred in an optimal production. The minimum amount of electricity the grid needs to cover at any given time is called the baseload. The baseload power needs to be run consistently and should provide a stable and reliable energy source. Therefore, normal selections for baseload power sources are nuclear- and coal-fired power plants. However, the energy demand fluctuates substantially through a day, so baseload power is not suitable to cover the whole electricity demand on its own. The power plants that are used in order to meet the fluctuations are called peaking power plants. Peaking power plants have in common that they are dispatchable and the energy output can be rapidly changed. The most common peaking plants are gas-driven turbines, due to short time required for ramping up their energy generation (Lund et al., 2015).

Electricity is measured and billed by the unit kilowatt hour (kWh) or in grater units like megawatt hours (MWh) (10^3 kWh), gigawatt hours (GWh) (10^3 MWh) and terawatt hours (TWh) (10^3 GWh). If power is used at a constant rate for a specific duration, the total energy amount is then the power in kW multiplied with the time in hours, resulting hence in kWh. Power and generation capacity are expressed in a unit for power given in watts or joules per second, while the energy is measured in watt hours or joules. A watt hour equals 3,600 J. Equation (1) below can be used for calculating the energy, when the power and time is known.

$$E = \eta \left(\frac{P}{\mathrm{W}}\right)\left(\frac{t}{\mathrm{h}}\right) \mathrm{Wh} \tag{1}$$

In the equation E is the energy expressed in watt hours, η is the dimensionless efficiency, P is the power in watts and t is the time in hours. When converting between the two units, the amount of time that has passed has to be known. When talking about annual electricity generation or consumption, the number of hours in a year is 8,760. As an example, a power plant with the capacity of 100 MW and an efficiency of 0.7 will annually output:

$$0.7 \cdot 100 \text{ MW} \cdot 8{,}760 \text{ h} = 613{,}200 \text{ MWh} = 613.2 \text{ GWh}.$$

2.3. Fossil fuels

Fossil fuels are hydrocarbon deposits that have formed through the fossilisation of ancient organisms. They are rich on coal and have a high energy content. The high energy content originates from the solar energy plants gathered and transformed to chemical energy before the petrification took place. Fossil fuels are non-renewable or slowly renewable and therefore, when consumed, are depleted more quickly than new fuel is generated. The most common fossil fuels are oil, natural gas and coal (IEA, 2019). Peat is a disputed energy source and depending on organisation the classification. For instance, the United Nations Framework Convention on Climate Change (UNFCCC) classifies peat as a fossil fuel (Gritsevskyi, 2008), while the Intergovernmental Panel on Climate Change (IPCC) classifies peat as neither a fossil fuel nor a renewable energy source, but something in between. However, they state the emissions from peat are similar to the emissions of fossil fuels (Eggelston, Buendia, Miwa, Ngara & Tanabe, 2006). A third classification, slowly renewable, can be found among the shareholders in the peat industry (Ylönen & Simola, 2012). For the sake of simplicity, in this thesis peat is considered as a fossil fuel in accordance with the recommended definitions by Gritsevskyi (2008).

Fossil fuels are used as primary energy sources, i.e. they are directly burnt. When burnt they release the energy they have stored and, thus, emit great amounts of heat. The heat is then used to evaporate water and the steam rotates a turbine. The turbine then rotates a generator which outputs electricity. Fossil fuels have several downsides that have to be taken into account. Combustion of them release significant amounts of different emissions and pollutions, such as greenhouse gasses and particulate matter. This makes the electricity sector a major pollutant (IEA, 2019). Also, only a handful of countries have natural fossil fuel sources, which makes few countries self-dependent when it comes to fossil fuels. The rest of the world depend on the countries with fossil fuels, which makes national energy systems a pawn in global politics. Finally, due to the non-renewable nature of fossil fuels the world will eventually run out of them since they are consumed much faster than new fuels are formed.

2.4. Nuclear power

Nuclear power refers to the process of obtaining energy from nuclear reactions. There are two kinds of nuclear reactions: nuclear fission and nuclear fusion. Nuclear fission refers to the process in which the nucleus of a heavy atom is split into two or more lighter nuclei. Nuclear fusion, on the contrary, is the process when two or more light atomic nuclei are combined to form a heavier atomic nucleus and usually some surplus subatomic particle, neutron or proton. Both of these processes can be highly exothermic and release great amounts of energy. This is due to the changes in the strong interaction in the nucleus of the atoms. Of the two, only nuclear fission is used for commercial applications and the most used nuclear fuels are uranium 235 (^{235}U) and plutonium 239 (^{239}Pu) (Breeze, 2019).

In a nuclear power plant, electricity is generated using controlled nuclear fission reactions. The reactions release heat which is used to vaporise water. The vapor rotates a turbine, thus converting the heat energy to kinetic energy. The kinetic energy is then further converted to electric energy with a generator. The energy density is enormous in nuclear fuel, up to millions of times greater than in other fuels (Breeze, 2019). At the same time, the GHG emissions from nuclear power plants are negligible. On the downside, used nuclear fuel is highly radioactive and requires further treatment and management as well as isolation from the environment. The waste stays radioactive for up to millions of years, so short-term waste management solutions cannot be regarded as sustainable. Also, since both uranium and plutonium are minerals, they have to be mined form the ground. After the ore has been mined, it has to be enriched to the desired isotope, ^{235}U or 239 ^{239}Pu. Bothe of these processes are heavy on the environment, which should be considered in the total impact of nuclear power (Ewing, 2008).

2.5. Renewable energy sources (RES)

Renewable energy is an umbrella term for all the energy production that is based on RES (Eggelston et al., 2006). The renewability is generally defined as sources that naturally restore at a rational pace, e.g. under a human lifetime. These include energy harnessed from the sun, wind, water and the core of the earth, i.e. geothermal energy. Additionally, energy production based on use of biomass, like burning firewood or refining biomass into biofuels, is generally included in the RES (Gritsevskyi, 2008).

The benefits with RES when compared to fossil fuels is their ability to lessen pollutions and reduce emissions (Schlömer et al, 2014). Compared to nuclear power, which is also clean when it comes to emissions, renewable energy gives an alternative with none of the precarious waste and the risk of severe accidents with long-lasting effects. This makes RES an overall better alternative for preserving the natural balance on earth (Houghton, Jenkins & Ephraums, 1990).

The five RES that are the most relevant when it comes to commercial electricity generation and will be addressed in this thesis are photovoltaic solar-, wind-, hydro- and geothermal power as well as power generated from biomass. In the subsections below, the power generation principle and calculation formulas for them will be presented. This thesis will not immerse in the theory and neither historical aspects nor future possibilities of the energy sources will be explained in depth. Instead the general picture of the current state of technology, efficiency and storage need are given.

2.5.1. Solar Photovoltaics

Photovoltaics (PV) refers to the process of transforming sun energy, photons, to electric energy, electrons. This is done through the photovoltaic effect and the use of semiconducting materials. These semiconducting materials are gathered to solar cells which are connected to form solar modules and further form solar panels. Advantages of solar PV is low maintenance due to no moving parts and no emissions after commission (Bazilian et al., 2013). Worth noting is that PV is not the only solar technology out there, but currently it is by far the most efficient when it comes to electricity production (Breyer, Bogdanov, Komoto, Ehara, Song & Enebish, 2015). Since it has the highest efficiency, it is the only technology that is considered as a solar power source in this thesis.

Since the sunlight, that the solar panels absorb, are pure energy, the restricting variable in solar PV electricity generation is the intensity of the sunlight as well as the area of the panel. Due to this, the efficiency is generally expressed as fraction, or percent, of the incoming energy in the sunlight (Aggarwal, 2020). Earlier the solar cells have not been that efficient and electricity output has been very low. However, the increasing climate awareness and technology development have lowered the costs and increased the efficiency and the highest measured efficiency in a laboratory for monocrystalline silicon solar cells is as high as 26.1%. Further, the all-time highest measured value for a solar cell is as high as 47.1%. This is with a concentrated multijunction solar cell (National Renewable Energy Laboratory, 2019). Nevertheless, the highest measured values are not commercially sustainable due to the rare materials, experimental technology and the high investment costs of such panels. Instead, efficiencies in the mercenary solar panels are usually between 15% and 20%, with the most efficient panels at approximately 23% (Aggarwal, 2020).

2.5.2. Wind power

Wind power refers to when the power in wind is transferred to mechanical power in a turbine. In order to produce electricity, the turbine is connected to a generator which rotates as a result of the mechanical power from the turbine. Wind turbines are generally gathered to form windfarms. Depending on where the wind farms are placed, the wind power is divided into onshore and offshore wind power. As the names suggest, onshore wind power refers to the windfarms located on shore, i.e. on land, while offshore wind power is generated in windfarms offshore, at sea. Onshore windfarms are typically spread over a broad area and, thus, has an impact on the landscape. Also, if they are built in the countryside, they result in a loss of natural territory for some species. Offshore wind is generally stronger and more consistent and offshore windfarms also have less of a visual influence for the public. On the downside the maintenance costs of offshore wind power are noticeably higher than the maintenance costs of onshore wind power (Breeze, 2016).

Wind power generation depends on the wind conditions and the most important is naturally wind speed. This is because the wind power is proportional to the third power of wind speed. The equation for wind power output can be seen in Equation (2).

$$P_{wind} = \frac{1}{2}\eta\left(\frac{A}{\mathrm{m}^2}\right)\left(\frac{\rho}{\mathrm{kg/m}^3}\right)\left(\frac{v}{\mathrm{m/s}}\right)^3 \mathrm{W} \tag{2}$$

In the equation, P_{wind} is the output power in watts, A is the area the wind passes through, i.e. the area of the rotors, expressed in square meters, ρ is the air density in kilograms per cubic meter and v the wind speed in meters per second. In order to compensate for the friction and losses, a dimensionless efficiency rate η is introduced. The efficiency rate η is dimensionless. The efficiency for wind power turbines varies, but there is a theoretical maximum or an ideal turbine, the Betz limit or Betz's law. According to Betz (1920) the maximum kinetic energy in wind that can be converted to other forms of energy is 59%. However, since wind turbines have internal efficiencies, the real efficiency of the system is always lower than the maximum of 59%.

2.5.3. Hydropower

Hydropower means that energy is derived from the potential energy present in water at an elevated height. Water is led through a turbine and, as in wind power, the turbine rotates a generator which outputs electricity. Falling water is a result of when water condensates due to heat from the sun and then rains in places higher than the water level, thus giving the water a potential energy. The potential energy is further transferred to kinetic energy in streams and rivers (Egré & Milewski, 2002).

Electricity can be generated using natural sources, such as waterfalls. However, there are not that many waterfalls in the world, so in order to increase the capacity of hydropower, artificial water reservoirs have been built. Water reservoirs used for power generation are usually equipped with dams. The dams control the water flow and, thus, control the power generation. By doing this, the seasonal variations are smoothened, and the energy can be used when needed (Sharma & Singh, 2013). Nevertheless, the dams have significant environmental impact. Since they are used to alternate the natural flow, the whole ecosystem is impacted. Further, when designing dams, the worst-case scenario, i.e. flooding, must be taken into account. This is done by building a bypass for the water to flow around the dam and leaving an uninhibited area around the water reservoir (Egré & Milewski, 2002).

The potential energy of the water is naturally dependent on the height deviation from the lower water level, but also the flowrate has an impact. The power output of a hydro turbine can be calculated with Equation (3) (Sharma & Singh, 2013).

$$P_{hydro} = \eta \left(\frac{\rho}{\mathrm{kg/m^3}}\right)\left(\frac{\dot{V}}{\mathrm{m^3/s}}\right)\left(\frac{g}{\mathrm{m/s^2}}\right)\left(\frac{\Delta h}{\mathrm{m}}\right)\mathrm{W} \tag{3}$$

P_{hydro} is the power output of the turbine in watt, ρ is the density of the water in kilogram per cubic meter, $\dot{V}$ is the volumetric flow of the water in cubic meter per second and Δh is the height of the fall in meters. Since all turbines have an efficiency rate due to losses in the energy transferring process, the equation is multiplied by a dimensionless efficiency factor η. Information on efficiencies on hydropower plants in the range of 60 – 80% for small hydropower plants can be found (Paish, 2002) while bigger plants can have efficiencies as high as 95% (Gürbüz).

2.5.4. Geothermal energy

Geothermal energy is about the thermal energy generated and stored in the interior of the Earth as a result of radioactive decay that takes place in the core of the planet (Barbier, 2002). The temperature in the core is significantly higher than the temperature of the matter surrounding it, resulting in a temperature gradient averaging 2.5 – 3°C/100 m, but in some places the gradient can even be up to over ten times greater (Dickson & Fanelli, 2003). This energy can be harnessed and used in heating of buildings and power generation (Barbier, 2002).

Geothermal energy is primarily accessible in hot water and steam that is transported to the surface, like in geysers and hot springs. The energy can also be accessed by drilling a channel in the earth through which water is circulated (Barbier, 2002). The water heats up and vaporises to steam due to the excessive temperature in the channel. The steam is then led through a turbine which rotates a generator that outputs electricity. However, the transition from geothermal energy to electricity is not completely trivial because of the relatively low operating temperatures. Due to the low temperatures, electricity generation with geothermal energy requires steam cycles that are optimised for low to moderate temperatures. Examples of such processes are the Kalina cycle and the organic Rankine cycle (ORC) (DiPippo, 2005). Other applications for geothermal energy can be found in district heating. In that case, the heated water can be used as such, or the hot stream can be led through a heat exchanger to heat a colder stream (Barbier, 2002).

Running the geothermal plant does not generate any costs apart from the pumping costs. However, the capital investments are significant, and the risk of failure is severe, up to 20%. Further, polluting gasses might be released from the ground and different toxic elements might be dissolved in the water that is pumped. Also, in seismic areas, drilling might affect the land stability and cause earthquakes (Barbier, 2002; Dickson & Fanelli, 2003).

2.5.5. Energy from Biomass

Biomass is all organic material that originates from plants and trees. This includes all land- and water-based vegetation as well as organic waste. Through the photosynthesis the organic matter has stored the energy of sunlight in chemical bonds as carbohydrates.

When the bonds are broken by actions like digestion, combustion or decomposition, the stored energy is released. Biomass can be used directly in a combustion process as a primal fuel, like in bio-waste heat plants, or transformed to substances which can be used to replace fossil fuels in fuel or gas power plants, namely biodiesel and biogas (McKendry, 2002a).

As such, the biomass is burnt in order to vaporise water and generate steam which rotates a generator via a turbine. The energy content of dry biomass is almost the same regardless of the biomass species, 17 – 21 MJ/kg. All biomass can be utilised in combustion plants (McKendry, 2002a). However, since some species have a high moisture content (>50%), it is not feasible to use all species unless they can be pre-dried. The biomass with a high moisture content is better suited for biological conversion processes (McKendry, 2002b). Biomass can also be specifically farmed for energy generation. Such plants should harvest a high amount of dry material per land used for growing them. This reduces both the necessity for farming land and the cost of such farming. Further, the energy that can be gained from the crops have to be more than the energy that has to be put into the farming process (Chum & Overend, 2001).

In order to convert the biomass to gaseous or liquid bio fuels some plants are better suited than others. The different available processes can be roughly divided into two categories, thermo-chemical conversion and bio-chemical conversion. In thermo-chemical conversion, the biomass is treated with heat in order to receive the desired product. The main technologies are gasification and pyrolysis. Bio-chemical conversion utilizes the chemical compound of the biomass in order to derive different compound that can be used in further applications. The main types of bio-chemical conversion are fermentation, anaerobic digestion and mechanical extraction (McKendry, 2002b).

2.6. Energy storage

When planning for energy production, energy supply and demand must meet at all given times. This is not an easy task since both the supply and demand vary over time, often in a cyclic manner, but sometimes the variations are highly unpredictable. High variations in demand require a high flexibility on the production side. Several of the RES suffer from an uneven availability, thus, causing a situation with supply gaps during which the demand is higher than the current production (Child & Breyer, 2016a; Lund et al., 2015). The fact that the supply varies with no correlation to demand makes the task even harder (Richardson, 2013). Usually the demand peaks are covered using fossil fuels in so called peaking plants (Child & Breyer, 2016a). These plants are commonly based on gas, but also other types exist. These peaking plants work like giant generators, where an engine drives a turbine and produces electricity for the grid. Peaking plants are characterised by a very high ramp up rate and will require only a short time to ramp up to full production (Lannoye et al., 2010). In order to achieve a higher grade of renewable energy these peaking plants would need to be replaced by other solutions. Thus, several studies (Child & Breyer, 2016a; Lund et al., 2015) suggest that the variability of the RES makes energy storage solutions a prerequisite for future energy systems that rely on renewable energy in a bigger scale.

Electricity cannot be stored directly, but has to be transferred to another form. The different possibilities of conversions are to potential energy, kinetic energy, thermal energy or chemical energy. The biggest limitation with the different storage technologies are the losses in the conversions. It is a two-stage cyclic process when electricity is stored and then reconverted from storage, making the losses in the conversions cumulative (Dell & Rand, 2001). Different energy storage technologies have been developed to replace fossil fuels when renewable energy production is not enough to meet the demand, and at the moment they are in a research and test phase (Zakeri & Syri, 2015). As it seems now, the most relevant of the energy storage technologies are: pumped hydro energy storage (PHES), compressed air energy storage (CAES), flywheels, thermal energy storage (TES), power-to-gas (P2G) and power-to-hydrogen (P2H), different kinds of batteries and vehicle-to-grid (V2G) connections. These technologies are presented briefly in own sub-sections below.

2.6.1. Pumped hydro energy storage (PHES)

PHES is the most mature and widely spread energy storage technology in the world. PHES is based on the potential energy of water. Two water reservoirs at different altitude are needed and the reservoirs are connected via a sluice-gate. During high electricity supply, power is used to pump water from the lower reservoir to the higher, thus, adding potential energy to the water. This energy is released in peaking times by opening the interconnecting channel. The water will steam to the lower reservoir through a hydro turbine in a similar way as in conventional hydro power plants. The only requirements for the system are a water supply and sufficient difference in elevation. The elevation difference can also be achieved with digging the lower reservoir underground in case natural elevation is not present (Dell & Rand, 2001; Lund et al., 2015; Schoenung & Hassenzahl, 2003). With regards to the required pumping power, reported efficiencies the recovered power for PHES varies from 65 – 85% (Egré & Milewski, 2002; Lund et al., 2015).

2.6.2. Compressed air energy storage (CAES)

In CAES air is compressed at high pressure into a storage during off-peak periods. The air is then expanded through a turbine or a series of turbines at peak demand. Since the air in CAES is compressed the storage technology utilizes potential energy. Due to the direct use of gas turbine technology, CAES is reliable and easy to maintain (Cavallo, 2007; Lund et al., 2015; Schoenung & Hassenzahl, 2003). The storage medium can be a salt cavern, empty mine or aquifer (Cavallo, 2007; Lund et al., 2015). Since the storage is hidden, CAES has less impact than PHES on the surface environment (Swider, 2007). Further, efficiencies of CAES plants are high and numbers up to 70 – 80% can be found in literature (Lund et al., 2015).

2.6.3. Flywheels

Flywheels are wheels with a high moment of inertia (MOI). They are designed to store energy as kinetic energy. The wheel is put into rotation with an electric motor, and due to the high MOI the wheel continues to rotate after the external power source is disconnected. Electricity is covered from storage by running the motor as a generator, which causes the wheel to slow down (Lund et al., 2015). The energy that is stored can be calculated with the formula for kinetic energy, Equation (4).

$$E_{kinetic} = \frac{1}{2}\left(\frac{I}{\mathrm{kg\ m^2}}\right)\left(\frac{\omega}{\mathrm{s^{-1}}}\right)^2 \mathrm{J} \tag{4}$$

In the equations $E_{kinetic}$ is the energy stored in joules, I is the moment of inertia in kilogram meters squared and ω is the angular velocity in unit of angle per second. Angles are dimensionless so only per second remains. The MOI differs depending on the design of the wheel (5).

$$I = k\left(\frac{m}{\text{kg}}\right)\left(\frac{r}{\text{m}}\right)^2 \text{ kg m}^2 \tag{5}$$

The MOI, I, is dependent of the shape factor k, mass, m, in kg and radius of the wheel, r, in meters. Substituting the MOI from Equation (5) into Equation (4) results in Equation (6) for a solid flywheel.

$$E_{kinetic} = \frac{1}{2}k\left(\frac{m}{\text{kg}}\right)\left(\frac{r}{\text{m}}\right)^2\left(\frac{\omega}{\text{s}^{-1}}\right)^2 \text{ J} \tag{6}$$

Thus, the amount of energy stored is dependent of the flywheel and the radius to the second power as well as the square of the angular velocity. In order to mitigate the effects of air drag and friction, the flywheels are often installed in vacuum with low-friction bearings (Dell & Rand, 2001). Despite these aspects, flywheels have a self-discharge rate of about 0.5% of stored energy per hour (Lund et al., 2015). Still, the reported efficiencies for flywheels are as high as 95% (Schoenung & Hassenzahl, 2003). Nevertheless, the storage capacity in flywheels is quite modest (Dell & Rand, 2001). and due to this, flywheels are not feasible long-term storage solutions. Instead they are suitable for smoothing the grid output, hence, increasing grid efficiency on a short-term.

2.6.4. Thermal energy storage (TES)

Storing energy in a thermal storage can be accomplished with various different technologies. The storage can either be short term, balancing hourly differences, or long term, for seasonal cooling or heating purposes (Lund et al., 2015). An obvious use of the stored heat is for heating and cooling purposes, but TES can also be used for electricity applications. Since the temperatures in TES are low, electricity generation from the heat stored in TES can be achieved through the Kalina or ORC cycle. (Laing, Bahl, Bauer, Lehmann & Steinmann, 2011). A major downside of such thermal-to-electricity storage cycles are the low recorded efficiencies, which are in the roundabout of 8% (Lolos & Rodgakis, 2009).

Heat can be stored both in sensible heat storage and latent heat storage. In sensible heat storage the storage media remains in same state and the temperature of the media increases with rising energy (Hasnain, 1997). Miscellaneous media and different liquids and solids are suitable for sensible heat storage. The technique is reliable and cheap and capacity depends on the mass and specific heat capacity of the media, as well as the initial and end temperatures as described in Equation (7).

$$\Delta U = \left(\frac{m}{\mathrm{kg}}\right)\left(\frac{c_p}{\mathrm{kJ\ kg^{-1}\ K^{-1}}}\right)\left(\frac{T_1 - T_2}{\mathrm{K}}\right)\ \mathrm{kJ} \tag{7}$$

In the equation above, ΔU describes the change in internal energy expressed in kilojoules, m the mass in kilograms and c_p the specific heat capacity in kJ/(kg K). T_1 is the start temperature and T_2 is the end temperature, both expressed in kelvin (Begeal & Decker, 2011).

Opposed to sensible heat storage, in a latent energy storage, the storage media undergoes a phase transition, most often a solid-liquid transition. In a phase transition the energy density is significantly greater than in sensible storage, thus, allowing less matter to store more energy (Hasnain, 1997). In order to achieve a phase transition at modest temperatures, specific phase change materials (PCM) have been developed (Kudhair & Farid, 2004). The energy density in PCM is very high, while the melting temperature is reasonably low. For instance, lithium nitrate trihydrate ($LiNO_3 \cdot 3H_2O$), which has a melting temperature at 30°C and melting enthalpy 296 kJ/kg. A close to ambient temperature melting point and high latent heat makes $LiNO_3 \cdot 3H_2O$ a remarkable PCM to use in energy storage applications (Mehling & Cabeza, 2008). Energy storage in thermal energy is also able to reduce the emissions that would be generated in case fossil fuels were used instead for the heat generation (Kiviluoma & Meibom, 2011). Further, TES is an energy storage technology, which is expected to increase the use of RES in the future (Lund et al., 2015).

2.6.5. Power-to-gas (P2G) and power-to-hydrogen (P2H)

In P2G and P2H power is used to produce gas when the energy supply is higher than the demand. This is due to that gas can be stored as such, while electricity cannot. The gas can then be taken from storage and used whenever the energy demand overtakes the supply. There are two main methods, hydrogen production and gas production. In the hydrogen production, hydrogen (H_2) is produced by electrolysis of water. The H_2 can then be stored and converted back to electricity in fuel cells (Lund et al., 2015).

When producing gas, it is done in a two-step process. First, H_2 is produced by electrolysis of water. Then, H_2 is combined with CO_2 to form methane (CH_4), in accordance with the Sabatier reaction. The Sabatier reaction is an exothermic reaction that requires temperatures over 300°C for initiation (Sabatier & Senderens, 1902). The formed CH_4 is also known as synthetic natural gas (SNG) and can be used as a substitute for natural gas in gas plants to generate electricity when needed or it can be stored as gas waiting for future needs. Since the process requires energy as an input, there is an efficiency in both stages that needs to be taken into account when planning for P2G storage. The losses are dictated by the efficiencies of 70% and 78% for the first respectively the second stage. This gives a total efficiency for P2G of 55% (Götz et al., 2016).

2.6.6. Battery technology

A secondary galvanic element, or more commonly a rechargeable electrochemical battery, is an example of a chemical energy storage technology. A battery consists of two electrodes with different electron affinities, the cathode and the anode. When charging a battery, external voltage is applied in order to drive electrons in an “upstream” direction, to the electrode with the lower affinity, the anode. When discharging the battery, electrons are allowed to move in their natural direction to the electrode with higher affinity, cathode (Ferreira, Gardeb, Fullic, Klinga & Lopes, 2013). The capacity, power density and costs of a battery depends on the materials selected for the electrodes. All the different types of batteries have type specific pros and cons. Type specific issues are for instance toxicity (nickel-cadmium), need of rare minerals (nickel-metal hydride), high self-discharge rate (nickel-metal hydride) and corrosion problems (sodium-sulphur). The lithium-ion battery, which is widely used in small appliances, lacks several of the issues the other battery types have. However, the lithium-ion battery is still way too expensive for large-scale power storage. Further, generally all batteries also suffer from a short functional lifetime and decreasing performance with increasing number of charging and discharging cycles (Lund et al., 2015).

2.6.7. Vehicle-to-grid (V2G)

V2G describes a system where electric vehicles (EV) communicate with the grid and function as a mobile energy storage. Most of the time our vehicles play an idle role and therefore they can be charged and discharged during this time with no impact on the owner of the vehicle. In a V2G system, when there is an electricity supply that is bigger than the current demand, all EV batteries would be charged in order to use all energy available and balance the energy system. When the demand exceeds the supply, electricity would be fed back to the grid from the EVs, thus providing additional capacity to the grid. The supported vehicle types are plug-in electric vehicles (PEV). This is due to these vehicles have a plug which can be used to connect them to the grid. The different PEV types that can be utilised in V2G solutions are: battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and fuel cell vehicles (FCV) (Lund et al., 2015; Richardson, 2013). In general, BEV have a significantly better life cycle fuel efficiency than internal combustion engine vehicles (ICEV) too. For BEV it can be as high as 60 – 70%, while it is for ICEV only 15 – 18% (Richardson, 2013). This is an aspect that foremost speaks for the electrification of the transport sector. Thus, V2G could also be a key factor in further integration of renewable energy to our grids. By the electrification, emissions and pollutions would decrease both from the energy source as well as the transport sector (Richardson, 2013). However, V2G is not alone efficient enough to add the required flexibility to the energy system as a whole. It is researched that PEVs work as a sufficient balancing mechanism for wind power penetration up to 50%, after that other technologies are needed to achieve the required flexibility (Ekman, 2011).

2.7. Emissions in the energy sector

The emissions from the energy sector are severe and over 35% of all the anthropogenic GHG emissions originate from the energy sector (Bruckner et al, 2014). Of the generation methods that are currently commercially available, RES have significantly lower emissions than fossil fuels (Schlömer et al., 2014). Since a majority of the world energy is generated with fossil fuels (IEA, 2019), the potential to reduce emissions is noteworthy. Consequentially, the emission reduction potential acts as an important driving force for the shift to renewable energy generation.

The emission intensity in the energy sector can be measured with grams of CO_2 equivalents (gCO_2eq). CO_2 equivalents is a measure on the impact that different GHG have on the acceleration of the natural climate change. CO_2 is the base unit, and other substances are expressed as an equivalent amount of CO_2 that would be needed to cause the same effect. In this way different emissions and their relative contributions can be easily compared, regardless the specific chemical composition, region or source (Schlömer et al., 2014). The CO_2 equivalents are derived when the absolute amount of a specific substance is multiplied with a value called global warming potential (GWP) (Shine, 2009). The GWP values are substance specific and for instance IPCC has listed the values for various substances (Myhre et al, 2013). Due to gasses decomposing over time in the atmosphere, the GWP also depends on time. The common time horizons used are 20, 100 and 500 years, of which the 100 years is the most commonly used (Shine, 2009) and the CO_2 equivalents in this thesis are also based on the 100-year GWP values. Worth to note about the concept of GWP is that even if it is not the only method for comparing emissions, nowadays it has become a default metric to measure the impact the different GHG emissions has on the atmosphere (Shine, 2009).

Emissions from the energy sector can be divided into two categories, direct emissions and life cycle emissions. Direct emissions are a metric that express the amount of emissions directly related to the usage of an energy source, for instance in a power plant or from traffic. Life cycle emissions, on the other hand, aim to take into account the whole lifespan of the energy source and include all the stages upstream and downstream of the actual exploitation of the source, as well as the indirect emissions that are present in the system (Dones, Heck and Hirschberg, 2000).

Table 1 presents the direct emissions as well as the life cycle emissions for the different energy sources in this thesis. The values are mainly from the climate change mitigation report by IPCC (Schlömer et al., 2014), with the exception of oil and peat, which were not mentioned in the report. The values from the IPCC report are the median values, so the calculations later in the thesis would not be too optimistic or pessimistic. The information for oil was found in other literature (Dones, Heck and Hirschberg, 2000), but no tables with both emission values for peat were found, thus, for this thesis they are assumed to be same as for coal. This assumption is based on Eggelston et al. (2006), who wrote that "its [talking about the peat] greenhouse gas emission characteristics have been shown in life cycle studies to be comparable to that of fossil fuels" (p. 1.15, footnote 5). Coal is also most similar to peat in substance out of the other remaining fossil fuels presented in the table.

Table 1. Direct emissions and life cycle emissions of different energy sources

Energy source	**Direct emissions [gCO_2eq/kWh]**	**Life cycle emissions [gCO_2eq/kWh]**
Oil	775 *	880 *
Gas	370	490
Coal	760	820
Peat	760 †	820 †
Nuclear	0	12
Solar PV	0	48
Wind power	0	12
Hydropower	0	24
Geothermal energy	0	38
Biomass	N/A ‡	230

Values from Schlömer et al. (2014), except for oil and peat

* From Dones, Heck and Hirschberg (2000)

† Assumed same as for coal

‡ Direct emissions from biomass combustion are significant, but the atmospheric CO_2 stays the same due to growing plants absorb CO_2. Note from Schlömer et al. (2014).

As it can be seen from Table 1, the direct emissions from nuclear power and the RES are equal to zero, at the same time as the fossil fuels, i.e. oil, gas, coal and peat, present high emission values. Basically, this means that neither nuclear power nor RES directly consume any substances that would affect the natural balance of the atmosphere. Since the life cycle emissions take into account the whole process, not only the energy generation, nuclear power and RES will also show positive values. Nevertheless, the values are again significantly smaller than the corresponding emissions for fossil fuels.

According to the numbers, any fossil fuel that is replaced by RES will result in lower emissions for the system. This is true for both types, direct- and life cycle emissions.

The values in Table 1 are applicable for continuous power generation, while for peaking power generation the values are much higher. Vattenfall (2019) suggests life cycle emissions over 2,200 gCO2eq/kWh and 1,600 gCO2eq/kWh for gas and oil based peak generation respectively. The severe increase is due to higher emissions originating from the construction, maintenance and dismantling of a peaking power plant (Vattenfall, 2019). Further, peaking power generation also has lower efficiencies than base power generation (Lund et al., 2015). This rises the emissions related to the power plant operation, which means higher life cycle emissions.

Trees and plants act as a natural carbon sink, since they use carbon dioxide (CO_2) as a reactant in the photosynthesis. When the biomass is consumed, it releases various chemical substances, including CO_2. However, this CO_2 is quite different from the CO_2 from fossil fuels. When fossil fuels are consumed, the CO_2 is taken from a rest and reintroduced to the system, while the CO_2 in biomass is already a part of the carbon cycle. This means that even if energy production from biomass releases CO_2, the overall balance remains the same, as long as new plants and trees are planted to replace the harvested biomass. In this way, the CO_2 is then absorbed by plants and trees and returns to the cycle (McKendry, 2002a). Some argue also that combustion of biomass causes other pollutions and particle emissions. However, Springsteen, Christofk, Eubanks, Mason, Calvin and Storey (2011) argue in their study that biomass which is used as fuel in industrial applications produce less particles and pollutants than the open burning in wildfires and open field fires. This is mainly due to the cleaner burn in the more favourable burning conditions that industrial applications offer.

2.8. Political means to control the electricity generation

The energy system, and more specifically for this thesis the electricity generation, is an object for political decision-making. National governments have generally two ways to go. They can push a policy that prohibits a kind of electricity production, or a remuneration policy that rewards the producers of a certain type of electricity (Haas et al., 2004). In order to meet the emission and CO_2 requirements, several nations are banning energy generation with fossil fuels by law. However, these bans are not immediate, but instead followed by a period of phasing down before a total phase out can be realised. Problems with this kind of policy is that if there is no existing substitute, they are not possible to carry out without additional investments (Green & Staffell, 2016). Remuneration policies, on the other hand, are instantaneous and instead of banning anything, they encourage new installation of renewable energy by the promotion of profitable investments in renewable energy. The regulatory methods can be divided in to two categories, price-driven and capacity-driven methods. In the price-driven methods, the price of electricity is set and then the market determines the quantity. On the contrary, in capacity driven methods, the quantity is first set and the price is decided by the market (Haas et al., 2004). The four major types of programs used to encourage renewable energy production are: feed-in tariffs (FIT) and tax incentives, both price-driven methods, and green certificates and competitive bidding, both of which are capacity-driven methods (Haas et al., 2004; Sarasa-Maestro, Dufo-López & Bernal-Agustín, 2013). The costs of remuneration policies are generally paid by the electricity consumers, so they should always aim to minimise the economic strain set on the public (Haas et al., 2004). Below a short presentation of the different political control methods that were mentioned.

2.8.1. Feed-in tariff (FIT)

The type of remuneration policy which is considered as the most effective, when it comes to promoting for investments and development in RES, is FITs. The central principle of FITs is that the government obligates the transmission system operators to feed in all the produced renewable energy at politically governed prices. In this way, the producers are guaranteed a fixed price, for a specified period of time, for specified types of electricity production. The electricity prices that are offered, may vary depending on the technology that is used, the capacity of the plant, location, and other project-specific variables. The value of the tariffs might also decrease over time. The tariffs may be either fixed tariffs, where the price is set above the market price, or as a bonus tariffs, which are added to the prevailing market price. The tariffs are intended to cover for the disadvantage derived from the use of RES (Couture & Gagnon, 2010).

2.8.2. Tax incentives

Tax incentives includes all the tax-related actions a government can utilise in order to make RES more attractive investments. The different actions comprise of reduced taxes, which help the producers to generate profit, tax credits, which make some of the revenue object for deduction, and accelerated depreciation, which result in less taxable income in the early years of the operation. All of these gives the investors a greater yield than the investment normally would, thus, making these investments more appealing than without the tax incentives (Sarasa-Maestro, Dufo-López & Bernal-Agustín, 2013).

2.8.3. Green certificates

Another possible system to steer the electricity generation is green certificates. Under it, the government aims to control the ecological effectiveness by ensuring a certain amount of the generated electricity is generated using renewable sources. In order to achieve this, the producers, distributors or consumer are either obligated to produce or buy a certain amount of the renewable electricity. The amounts are expressed as absolute values or as quotas. The certificates are issued according to renewable electricity generation. The producer has then two different sources for income. First, when selling the electricity to the market at the market price, and second, when selling the earned green certificates to the certificate market. Since renewable energy generation is generally more expensive than the use of fossil fuels of nuclear power, the producer is likely to make a loss. In order to make up for this loss the green certificates are sold at a price that gives the producer a profit. A separate certificate controlling authority is generally needed in order to make the system work in practice (Ringel, 2006).

2.8.4. Competitive bidding

In competitive bidding, the government holds public auctions for set amounts of electricity, which must be generated annually. Different projects will then tender with the lowest price they will accept for their output, and the project that gives the lowest price wins. The government does not fund the building of the production facilities, but instead they are obligated to buy all the auctioned output for the price that won the bidding. The producers have to take in to account the building expenses and the limited time of the guaranteed price they get. When the time is up, there is no assurance on the price or amount they will sell, since both are determined by the market at that point (Toke, 2015).

3. The current state of the electricity system in Finland

3.1. The Finnish electricity system

Finland is a highly industrialised nation in the northern hemisphere. Finland also has four seasons, so both the periodic and everyday variations in energy consumption can be severe. Further, the high share of industries sets its own requirements on the energy system. Industries demand a reliable energy supply and due to the high standards of living set by the inhabitants, the energy sector must provide electricity of high quality both to the industries and individual consumers (Child & Breyer, 2016a).

The high-voltage grid in Finland is operated and monitored by Fingrid, a Finnish public limited company. The high-voltage grid has an essential role in the Finnish energy system, since the energy system is a “trunk” network that all the suppliers and consumers are connected to like branches. Since Finland is such a widespread country with great distances, the transmission system consists of over 14,000 kilometres of 400, 220 and 110 kV transmission lines and more than 100 substations (Fingrid, 2019a).

The Finnish electrical grid is a part of the inter-Nordic power system. Besides the Finnish power system, the inter-Nordic power system consists of the power systems of Sweden, Norway and eastern Denmark. The inter-Nordic power system is further connected to the power system of Continental Europe. The connection links are high-voltage direct current lines. Additionally, high-voltage direct current lines connect the Finnish electrical grid to the grids of Russia and Estonia (Fingrid, 2019a).

The electrical grid serves both electricity suppliers and consumers, thus giving both parties the opportunity to trade electricity on a nation-wide level as well as across national borders (Fingrid, 2019a). The grid capacity in Finland is much higher regarding the capacity to import compared to the capacity to export electricity (Child & Breyer, 2016b). This is also shown in the statistics of electricity consumption. In 2018 Finland used a total of 87.5 TWh, of which 20 TWh (23%) was net imports, the imports subtracted by the exports. Finland imports mainly from Sweden and Russia. The export of electricity was only roughly 2 TWh, essentially to Estonia (Statistics Finland, 2019), leaving the total imports around 22 TWh.

3.2. Electricity consumption in Finland

In 2018 the total electricity consumption in Finland was 87.5 TWh. This is about 2.5 TWh more than in 2017. Of the 87.5 TWh, industry used 47% (41.1 TWh) and other applications such as agriculture, households and services used 50% (43.5 TWh). The remaining 3% consisted of different losses in the electricity transmission process (Statistics Finland, 2019). Generally, the electricity consumption varies throughout the day, a higher consumption during daytime and lower in the night (IEA, 2018). Moreover, the electricity consumption also varies through the year. The cold and dark winters cause a natural increase in the energy demand in the form of increased heating as well as added electricity usage (Child & Breyer, 2016a). Since the Finnish industries consume a considerable amount of electricity, also the industrial production cycles affect the variability on the demand side (IEA, 2018).

3.3. Current state of non-renewable electricity generation in Finland

The total electricity consumption in Finland, was 87.5 TWh in 2018. Of this, 20 TWh was net imports, leaving the total production at 67.5 TWh. Of the electrical energy production 46.2% (31.2 TWh) was done by RES, primarily hydropower and with biomass as well as wind power, 32.4% (21.9 TWh) by nuclear power and 20.9% (14.1 TWh) by fossil fuels, mainly gas, oil and peat. The remaining 0.5% (0.3 TWh) is categorised as other energy sources (Statistics Finland, 2019). This last category could be problematic, since no generation source is mentioned. However, for the cause of this thesis, the impact from the 0.3 TWh from other sources will be neglected in the calculations.

3.3.1. Fossil fuels

Finland lacks the resources needed for energy production in means of fossil fuels, except for peat. This means Finland must import all oil, gas and coal that is used in energy production. Finland imports fossil fuels mainly from Russia (IEA, 2018). Coal and gas accounted for the major part of the fossil fuel electricity production with 8.1% respectively 6.1% of the total generation in 2018. Peat, which exact classification depends on the organization, was responsible for 4.8% of the annual electricity production, while oil was used only for 0.3% of the total generation. A share of 1.7% is classified as other fossil fuels, so the total stake of fossil fuels of the electricity production was 20.9% (Statistics Finland, 2019). However, the importance of fossil fuels in Finnish electricity generation has decreased substantially during the last decade. This is mainly due to the increased climate awareness and a higher integration of RES (IEA, 2018).

3.3.2. Nuclear power

The power generation in Finland relies on nuclear power as baseload (IEA, 2018). Nuclear power has a total capacity of 2,794 MW in two nuclear power plants with two reactors each, two 890 MW reactors in Olkiluoto and two 507 MW reactors in Loviisa (Energy authority, 2019). Considering the current electricity generation of 21.9 TWh, the total annual efficiency of the nuclear power is 0.89. Additionally, a fifth reactor of 1,600 MW, Olkiluoto reactor 3, is approaching the end of construction and is planned to commission in November 2020 and start electricity generation for the grid in Spring 2021 (Soisalon-Soininen, 2019). This latest reactor has however not come without problems. Olkiluoto 3 has met severe construction delays and cost overruns (Child & Breyer, 2016b). The reactor was originally planned to be ready to use in 2009, so the reactor is over a decade behind schedule (Lassila & Hartikainen, 2019). At the same time the budget has gone from the planned €3 billion to €8.5 billion (Koistinen, 2012).

The operation and safety of the nuclear power plants is overseen by the Radiation and Nuclear Safety Authority (STUK). Besides monitoring, STUK also has the authority to control the operation licenses of the nuclear reactors. When it comes to the existing nuclear power plants, the operating licence for the two reactors in Loviisa will expire in 2027 and 2030, for reactor one and two respectively. The operating licences for the two existing reactors in Olkiluoto and the third reactor which is nearing completion will expire in 2038. However, the operating licence for these three reactors might well be extended if they fulfil the required safety requirements (STUK, 2019). Finland does not have enriched uranium at all, so the nuclear fuel has to be imported from abroad. Finland imports all of its nuclear fuel in the form of manufactured fuel assemblies, mainly from Western Europe and Russia (IEA, 2018).

3.4. Current state of renewable electricity generation in Finland

Finland has committed to several emission targets and environmental programmes and RES play a central part in achieving them (Finnish Government, 2019). Finland has already a substantial amount of RES integrated into the current energy system and when it comes to electricity production renewables accounted for 46.2% (31.2 TWh) of the total electricity generation in 2018 (Statistics Finland, 2019). The most relevant RES in use are biomass- and hydropower. The availability of these two are relatively evenly distributed over the seasons. Nevertheless, the high latitude translates to significant daily and seasonal variations in the output of some renewable energy like solar- and wind power (IEA, 2018). These might offer a possibility in the future, but at the moment they are mainly just responsible for excess production in a smaller scale (Statistics Finland, 2019). Geothermal energy is not utilized at all in Finland when it comes to electricity production (Kallio, 2019) and therefore geothermal energy is excluded from the subsections below.

3.4.1. Solar PV

Due to the northern latitude of Finland, the solar irradiation varies significantly during the year. The irradiation is high during summer months with just short periods, if any, when the sun is down. The opposite is true for winter months, short days with sunshine of lower intensity (Child & Breyer, 2016a). This presents a major challenge and a need to find alternate resources during the wintertime (Child & Breyer, 2016b). “Solar energy has not been harnessed in large scales in Finland” (Zakeri, Syri & Rinne, 2015, p. 250), so the current solar PV capacity in Finland is quite small, only one over 1 MW plant registered by mid-2019 (Energy authority, 2019) and just five over 0.5 MW plants (Child, Haukkala & Breyer, 2017). The total installed capacity is approximated to be 20 MW (Child, Haukkala & Breyer, 2017). The contribution of solar PV of the renewable electricity generated in 2018 was only 0.1% or approximately 0.1 TWh (Statistics Finland, 2019).

3.4.2. Wind power

Similar to solar PV, wind power is also object for serious seasonal variation. However, the power generation is, opposed to solar PV, greater during the winter months. This applies for both onshore and offshore wind power. (Child & Breyer, 2016a). Wind power is the third biggest source used in renewable electricity generation in Finland, and in 2018 wind power was accountable for 18.7% of the renewable electricity generation. This equals a production of 5.8 TWh (Statistics Finland, 2019). The installed capacity of wind power by mid-2019 in Finland was 2,034 MW (Energy authority, 2019). However, this capacity cannot be utilised to 100% due to the significant variations in the wind conditions. Holttinen (2005) claims the capacity usage in Finnish wind power during 2000 – 2002 was as low as 23%. When calculating from the installed capacity, the annual generation would be 17.8 TWh, given an efficiency of 100%. Compared with the realised production, this is equivalent to an annual efficiency of 33%. This difference might be due to bigger wind turbines and almost two decades of technical development in the field.

3.4.3. Hydropower

Of the RES in use, Finland has a sustainable part of hydropower. The current installed capacity if Finland is 3,240 MW (Energy authority, 2019). In 2018 hydropower was responsible for 42.1% of the renewable electricity generation in Finland, which translates to an annual production of 13.1 TWh (Statistics Finland, 2019). However, the annual generation with hydropower varies depending on the weather conditions during the year. This means that with the same generation capacity the generation has been different from year to year and a ten-year average, 2009 – 2018, has an annual average generation of 14 TWh (Statistics Finland, 2019). Hydropower has also a seasonal aspect since meltwater is dammed in the spring and reservoirs are kept relatively full until the winter when the cold weather causes an increasing energy demand (Child & Breyer, 2016a). If this could be done to all hydropower capacity, the hydropower capacity would be considered as fully flexible. However, such actions are not possible to perform on all hydropower capacity in Finland. It depends on the type of hydropower generation that is used (Sharma & Singh, 2013). In Finland the runoff-river hydropower plants dominate the generation (Child & Breyer, 2016a). A runoff-river hydropower plant is characterised by a very limited storage capacity (Sharma & Singh, 2013) and, thus, the Finnish hydropower is after all quite evenly distributed throughout the year.

3.4.4. Bioenergy

With abundant forest resources and an extensive forest industry Finland has outstanding qualifications for power generation with biomass (IEA, 2018). "Finland is one of the leading countries in biomass use for energy production" (Zakeri, Syri & Rinne, 2015, p. 248) and, thus, bioenergy is considered as the backbone of Finnish electricity generation (IEA, 2018). Bioenergy was accountable for 48.9% of renewable electricity generation in 2018 totalling at 12.1 TWh (Statistics Finland, 2019). Bioenergy includes power generated using biofuels, solid biomass, municipal waste and industrial waste. In recent years the use of biomass has grown. The increase in bio-based power generation has consequently reduced the contributions of coal and natural gas (IEA, 2018).

3.5. Emissions in the current electricity system

Regardless the high shares of RES Finland has already integrated into the electricity system, there is still a substantial share of electricity generation done with fossil fuels. The emissions in the current system are determined according to the generation from 2018, presented earlier in this chapter, and with the emissions for the different energy sources presented in section 2.7 Emissions in the energy sector. Worth to note is that the total emissions presented here are not necessarily the same as other scholars or that statistic might suggest. Possible differences arise due to possibilities to use other estimated emission intensities than the ones selected in this thesis. Lastly, the calculations in this thesis fail to take in to account the possible higher emissions in peaking plants, which might increase the total emissions in the system. The calculated emissions for the current system, expressed as megaton CO_2 equivalents (Mt CO_2eq, equal to 10^{12} gram CO_2 equivalents) are presented in Table 2. Geothermal energy is not included in the table since Finland does not have any electricity generation with geothermal energy.

Table 2. Direct emissions and life cycle emissions in current electricity system of Finland

Energy source	Generation 2018 [TWh]	Direct emissions [Mt CO_2eq]	Life cycle emissions [Mt CO_2eq]
Oil	0.2	0.16	0.18
Gas	4.1	1.52	2.01
Coal	5.4	4.10	4.43
Peat	3.3	2.51	2.71
Nuclear	21.9	0	0.26
Solar PV	0.1	0	0.00 *
Wind power	5.8	0	0.07
Hydropower	13.1	0	0.31
Biomass	12.1	0	2.78
Total	**66.0** †	**8.29**	**12.75**

* Value insignificantly small due to negligible solar PV generation 2018

† The share of the various "other sources", total 1.5 TWh, excluded

Since the are no direct emissions from the RES and nuclear power, the direct emissions from them are also zero in the Finnish electricity system. This means the only contribution of direct emissions originates from fossil fuels. This means that even though fossil fuels are responsible for 20.9% of the electricity generation, they account for all of the direct emissions. When it comes to the life cycle emissions, RES and nuclear power generation also have a contribution. The total ratio of life cycle emissions is that fossil fuels account for 73.1% of the total emissions, while the remaining 26.9% originate from generation with nuclear power and RES. However, the emissions from fossil fuels are still unproportionally large. The biggest contributor of emissions in both direct emissions and life cycle emissions is coal. Coal alone is accountable for approximately half of the direct emissions, 46%, and over a third of the life cycle emissions, 35%. Despite being classified as renewable, biomass has considerable life cycle emissions, nearly 22% of the total amount.

In the current electricity system Finland is dependent on imports of electricity. This means the emissions for the electricity system in Table 2 are too small. The table includes the emissions only from 66.0 TWh of generation, while the total demand would be 87.5 TWh. In other words, the 20 TWh of positive net imports as well as the 1.5 TWh from “other sources” are not included in the table at all. This is due to that the generation of the imported share is done outside the supervision of the Finnish energy system and, therefore, the energy source cannot be indisputably determined. Also, the energy source for the other sources are not defined and emissions cannot be determined based on the available information.

With regards to the ambitious goal of the Finnish government, to reduce total emissions by 55% below the 1990 levels, the life-cycle emissions should not be used for the calculations. This is due to Finland has interpreted the Kyoto protocol to include all emissions of specific gasses, but not the indirect emissions that are related to other generation (Statistics Finland, 2018). This makes the maximum emission reduction potential 8.29 Mt CO_2eq. This is achieved by having zero emissions in the electricity generation, i.e. no generation with fossil fuels. The GHG emissions in 1990 Kyoto protocol base value for Finland is 71.3 Mt CO_2eq (Statistics Finland, 2018). This means that in 2030 the emissions should be 32 Mt CO_2eq. In 2018 the total GHG emissions were 56.5 Mt CO_2eq (Statistics Finland, 2019), which means that even if the emissions in the electricity sector would be equal to zero, the total emissions would still be 48.21 Mt CO_2eq, or 16.21 Mt CO_2eq too much.

3.6. Finnish energy policy

In Finland the Ministry of Economic Affairs and Employment (MEAE) is responsible for the energy efficiency policy and the integration of the policies across the ministries and other institutions. Finland is a part of the EU and therefore takes part in the ambitious climate and emission targets that the union has set. In 2017, the Ministry published the National Energy and Climate Strategy for 2030 (MEAE, 2017), which outlines the actions that will allow Finland to reach the targets for 2030 set by EU. The Finnish strategy to achieve the GHG reduction targets are to decrease the use of fossil fuels and to replace it with RES. In order to do this the government has established several programs and incentives that steer the energy sector in a renewable direction. Below some of the major procedures that are used.

Finland is abandoning the use of coal as fuel in all energy production starting from May 1. 2029, with just a few minor exceptions (MEAE, 2017; Act 416/2019). Due to the ban companies have already started to phase out their coal consumption (IEA, 2018), which can already also be seen in the electricity generation statistics, only 8.1% (5.4 TWh) of the electricity generation in 2018 was done using coal (Statistics Finland, 2019). However, before we reach May 2029, this capacity should be substituted with other, renewable, energy sources.

Finland has introduced a FIT system for renewable energy generation. The system started in 2011 and aims to promote higher shares of renewable power generation. The system guarantees a market and a minimum price on the electricity generated in a power plant that is approved in the system for up to 12 years. The energy sources that were accepted to the subsidizing system were wind power and bioenergy, power plants running on biogas, forest chips and wood-based fuels (Act 30.12.2010/1396). Solar power was left out from the FIT system completely, supposedly because of the common misunderstanding that solar power is not feasible in the Northern Europe (Pasonen, Mäki, Alanen & Sipilä, 2012). Further, the FIT for new wind power projects ended in November 2017 but will continue for the earlier accepted plants (Act 30.12.2010/1396). The target is that in the future renewable energy production will be completely market-based and thus economically sustainable. During the transmission period there will be competitive bidding of different RES and technologies, and only the most cost-effective solutions will get financial support (MEAE, 2017).

In 2011, the Finnish government renewed the energy taxation to its current structure. Since then, the taxation has been based on three factors: the energy content of the fuel, the CO_2 emissions and the grade of local air pollution. The fuel tax is commonly referred to as the CO_2 tax. No major structural reforms have been performed since the establishment of the new requirements, only minor adjustments. What comes to the taxation of biofuels, there are three classification categories: biofuels that do not meet the sustainability criteria, sustainable biofuels and second-generation biofuels. The first category, the biofuels that fail to meet the required grade of sustainability, are object to same taxes as non-renewable fuels, like petrol. The sustainable biofuels are biofuels of first generation. These generally have an agricultural origin and they are object to 50% relief of the equivalent CO_2 tax as in fossil fuels. The second-generation biofuels are based for instance on waste or by-products, and they are fully relieved from the CO_2 tax (IEA, 2018).

Finland does not have the fossil fuels as natural resources and must import them instead. In order to ensure the status of peat as a competitive substitute for the imported fossil fuels, mainly coal, but still less competitive than wood-based fuels, the government has decided on a softer taxation for peat (MEAE, 2017). The taxation is not depending on the emissions, but instead promotes the use of peat by making it more cost-efficient than imported fuels. Peat has higher CO_2 emissions than coal or gas, which is against the emission targets set for 2030 and should be taxed accordingly (IEA, 2018). The Finnish Government is not united on the matter if the peat subsidized should be ended or increased in the future (Luukka, 2019). However, Finland does not have any plans for peat to be phased-out (IEA, 2018). Still, the current government states that they will strive to cut the current use of peat by half before 2030 (Finnish Government, 2019).

4. Future prospects for the electricity system in Finland

4.1. Electricity consumption

As stated earlier, the current annual electricity consumption in Finland was 87.5 TWh in 2018 (Statistics Finland, 2019). In the past, the electricity consumption increased solidly until it reached 2004, after which it has stabilised. Since 2004 the electricity consumption has varied between a low of 81.3 TWh in 2009 and a high of 90.4 TWh in 2007 (Statistics Finland, 2019).

In the future, the energy consumption is not expected to rise drastically. However, the electrification of the transport sector will inevitably result in an increase in the current electricity consumption, as more electric vehicles will result in an increased demand of electricity and consequentially push the numbers a bit higher (Child & Breyer, 2016b). According to studies by the Ministry of Transport and Communications (MTC), the Finnish transport sector should have 670,000 electric cars and 7,000 electric vehicles in the heavy transport in 2030 in order to achieve the long-term goal of zero emissions in the transport sector in 2045 (MTC, 2018). In 2018, cars were used for 14,000 kilometres on average while the heavy vehicles had an average of 70,000 kilometres (Statistics Finland, 2019). With approximated electricity demands of 0.2 kWh/km (Lassila, Kaipia, Haakana & Partanen, 2009) and 1.4 kWh/km (Earl, Mathieu, Cornelis, Kenny, Calvo Ambel & Nix, 2018) are considered for the cars and the heavy vehicles respectively, the total electricity demand of the transport sector would be 2.6 TWh, 1.9 TWh for the cars and 0.7 TWh for the heavy vehicles.

Another, unplanned, scenario that at actualisation will increase the electricity consumption significantly is an added use of electricity in heating. This could happen if Finns who now heat their houses with district heating decide to switch from it and start using different kinds of heat pumps instead, e.g. air source heat pumps and ground source heat pumps (Rinne & Syri, 2013). Reasons for a change of this kind could be the ever-increasing prices of district heating (Wilhelms, 2018) and the fast development and added efficiencies of heat pump technology. If the prices rise too much consumers will eventually consider different methods for heating of their homes and heat pump are a plausible substitute (Rinne & Syri, 2013). Both of the changes, the electrification of the transport sector as well as heating, would not result in any change of the total energy balance, but for the electricity sector they would mean an increased demand when comparing to the current state.

Different numbers of the predicted consumption for 2030 can be found in different research articles and reports. For instance, the Finnish state-owned Technical Research Centre of Finland (VTT) made an energy vision of the Finnish energy system in 2030. They anticipated an electricity demand of 82.5 – 96.5 TWh in 2030 depending on the decrease in GHG and state of technology (Kara, Hirvonen, Mattila, Viinikainen, Tuhkanen & Lind, 2002). In another study, a clean energy study, VTT estimated the consumption as 79 – 95 TWh in 2030, again depending on the grade of remodelling of the electricity system (Koljonen et al., 2012). Finnish Energy, which represents various stakeholders involved in the Finnish energy market, has made a vision for European electricity markets in 2030. They predict the 2030 electricity consumption in Finland to be 100 – 111 TWh. Noteworthy is that these numbers include a predicted share of 3 TWh for transport in 2030 (Viljainen, Makkonen, Annala & Kuleshov, 2011). Child and Breyer (2016b) made simulations of a carbon-free energy system for Finland for 2050 and assumed the total electricity consumption would be 95 TWh in 2020 and remain the same through 2050. This would consequentially mean a consumption of 95 TWh for 2030 too. However, they added the electricity demand of the transportation to these numbers. The approximated electricity demand for transport is 1.1 TWh and 10 TWh for 2020 and 2050 respectively. Linear regression would result in a 4 TWh demand for transport in 2030, leaving a total demand at 99 TWh.

The National Energy and Climate Strategy for 2030 by the MEAE estimates the consumption in 2030 to be 93 TWh (MEAE, 2017). This estimate is made with the assumption the transport sector uses 1.5 TWh electricity in 2030. The Finnish government has also made studies of their own. A report regarding energy taxation in the future, states the estimated electricity demand will be 92.1 TWh in 2030. They argue the slight increase compared to the current electricity demand is mostly due to increased number of datacenters and the electrification of the transport-, heating- and industrial sectors (Wahlström, Kaskela, Riikonen & Hankalin, 2017). As it seems, researchers are quite divided in this area. This is due to different assumptions for the future technologies and different methods used to acquire the estimates. Nevertheless, based on these numbers, the Finnish electricity demand in 2030 is in this thesis assumed to be close to the mean value of the different reports presented here, 95 TWh.

Further, when planning for a total self-sufficiency for the Finnish electricity generation, the peak load, i.e. highest momentary load, has to be taken in consideration. The all-time high, so far, occurred on 7 January 2016, when the required peak demand was 15,105 MW (IEA, 2018). The government estimates the peak load demand to grow to 15,300 MW for 2030 (MEAE, 2017). In order to be independent from energy imports, this means the energy system should have a minimum output capacity that matches the maximum peak demand.

4.2. A renewable future of the electricity generation

When considering an electricity production in Finland that requires a higher share of renewable sources, the maximum capacity for the different energy sources is of great interest. The maximum values from this subsection are considered as the upper limits in the calculations and the optimisation of the optimal energy blend later in the thesis. Since the electricity generation with RES varies from year to year, the level of 2018 generation will be referred to as a reference year.

4.2.1. Solar PV

Solar PV has not been earlier harnessed to the extent it would be possible. The high variability in solar irradiation sets some challenges for further integration. However, despite the high latitude of Finland, Child and Breyer (2016b) argues that the significant variations in solar irradiation and intensity during the year might not be an obstacle to the introduction of solar PV closer to the poles too. It is a known fact that the solar irradiation is lower in the Northern Europe than in Central- and Southern Europe. However, according to a study conducted by VTT, the differences are not as great as generally believed. They claim that the annual average of solar irradiation that reaches the surface is just over 900 kWh/m^2 in Finland. This is roughly the same as in Germany and Belgium, which are generally considered as good locations for solar power (Pasonen et al, 2012). Haukkala (2015) suggests that the main reason for the low utilisation of solar PV in

Finland might not be the lower irradiation rates, but that a wide range of different stakeholders, from individual consumers to politicians and energy companies, have self-interests which compete against or set restrictions for high capacities of solar PV. For instance, solar PV was not included in the FIT system that was introduced to promote building of new RES capacity (Act 30.12.2010/1396).

Finland is a country with a lot of space, so given the 900 kWh/m^2 and an efficiency of 20% for a solar panel, the possibilities are astonishing. Based on these numbers, an annual power density for solar PV would be 20.5 MW/km^2. This equals 180 GWh/ km^2 in annual generation. Not to be forgotten, the main environmental problem with solar panels is that panels shadow their beneath and therefore the land cannot be used for farming anymore (Kosonen,Ahila, Breyer & Albo, 2014). A solution is to place the solar panels on the roof. In that way the solar panels are not blocking other activities. Therefore, a fifty-fifty split is assumed when it comes to solar capacity installed on residential rooftops and larger ground mounted plants in accordance with the study by Child and Breyer (2016b). Zakeri, Syri & Rinne (2015) as well as Pasonen et al (2012) approximated the potential of solar PV installed on residential buildings in 2030 to be up to 3 TWh in annual production. This assumption was made with 60% of all the roof area of all the residential buildings facing south covered with solar panels. Given the timeframe of just over a decade the coverage of 60% seems optimistic, but possible. Given the density of 20 MW/km^2 for solar PV in the North, the land area requirement for a total electricity generation of 3 TWh in a year would be 16.7 km^2. This is just a tiny fraction of the total Finnish land mass of 303,901 km^2 (National Land Survey of Finland, 2019). This total capacity for solar PV of 6 TWh is hence considered the potential maximum capacity of solar PV integration in Finland for 2030.

4.2.2. Wind power

Even though wind power is responsible for a substantial part of the current electricity production, Finland aims to further rise the capacity of wind power (Finnish Government, 2019). There is a lot of room for expansion since, at the moment, the wind power density per land mass is very low in Finland. Finland has a big area, 303,901 km^2 of land (National Land Survey of Finland, 2019), and with a total wind capacity of 234 MW (Energy authority, 2019) this leaves the installed capacity per land mass at

0.77 MW/1000 km^2. As a comparison the average for EU was already 19.5 MW/1000 km^2 in 2010 (EWEA, 2011). This is more than twenty-five times larger, already a decade ago.

Limiting factors for wind power generation are naturally the wind conditions, but limitations are also set by technical limitations in the harsh climate, political bureaucracy as well as environmental and social aspects (Varho & Tapio, 2005). Onshore wind power is generally considered as ugly and disturbing for the natural environment (Child & Breyer, 2016b) and thus offshore wind power is the focus area for Finland (Kara et al., 2002). Finland is located between the Atlantic Ocean to the west, and the Eurasian continent to the east. The wind conditions are very different at the two compass directions. By studying the wind profile, it is clear the coast to the Atlantic Ocean has the highest wind rates (Finnish Wind Atlas, 2019). Also, considering the plans of concentrating on the building of offshore wind power, the western coast would naturally be better suited for this. However, offshore wind power has limitations set by the number of places available with waters shallow enough to make building of offshore wind economically viable and at the same time being out of sight to get the acceptance of the settlement to make it socially acceptable (Child & Breyer, 2016b). This will automatically increase the investment costs of wind power parks, since it would be cheaper to build somewhere there is an existing road system and an installed electricity infrastructure (Ahonen & Dukeov, 2016).

Assuming the coast is suitable for both onshore and offshore wind power, the area at use is enormous. This is even though the wind parks would be positioned away from the existing population centres. The costal line is about 4,600 km while the shore is approximately 1,100 km when measured with straight lines (Laurila & Kalliola, 2008). This means there is 1,100 km of suitable land and area and shallows with annual wind averages at about 9 m/s (on a height of 100 m above sea level) (Finnish Wind Atlas, 2019). Assuming a width of 10 km and a modest coverage of 20%, this gives a total useable area of 2,200 km^2. With an assumed wind turbine density of 8 MW/km^2, for standard 3 MW turbines with a hub height of 150 m in accordance with Child and Breyer (2016b), this would result in a total capacity of 17,600 MW. With regards to the utilisation rate of 33% of the current system, this would result in a total annual electricity generation of almost 51 TWh. This would cover more than half of the approximated Finnish electricity demand in 2030.

Since the wind resource nor the area is a limiting factor in the aggrandisement of the Finnish wind power, the limiting factor might be the building and commissioning rate of new wind farms. To examine this, the highest growth rate in Finnish wind power is used as reference. The highest growth occurred in year 2016, during which the capacity grew by 570 MW. The wind park average size has increased in Finland, from 173 kW in 1991 to 3.3 MW in 2017 (Finnish Wind Power Association, 2019). When translating this increase in average size to technological development in the field, the annual change is 120 kW. However, this change is so small that it is neglected in this case. An annual commissioning rate of 570 MW per year would mean an increase of 6,270 MW until 2030, starting in 2020. Added the existing capacity of 2,034 MW (Energy authority, 2019) this would result in a maximum of 8,304 MW of installed wind capacity by the end of 2030. Taking the current generation efficiency of 33% into account this results in an annual electricity generation of 25.5 TWh. In this thesis, this generation potential will be regarded as the maximum grade for wind power in 2030.

4.2.3. Hydropower

Currently Finland utilises a hydro power capacity of 3,240 MW (Energy authority, 2019). Nevertheless, the total potential capacity for hydropower is enormous. However, this capacity cannot be fully utilized at the moment. A lot of the hydro capacity is in rivers that are currently protected as environmentally sensitive areas and could cause sustainability issues. This means, only a fraction of the potential capacity is possible to exploit (Child & Breyer, 2016b; Zakeri, Syri & Rinne, 2015). Accordingly, in this thesis, the used hydropower capacity is not anticipated to rise from the current level. Since the annual energy generation depends on the weather conditions throughout the year, the generation will be different with the same capacity. In this thesis the average generation during a ten-year span, from 2009 to 2018, i.e. 14 TWh (Statistics Finland, 2019), will be considered as the potential generation capacity of 2030.

4.2.4. Biomass

Biomass is considered the foundation in the current renewable Finnish energy system (IEA, 2018) and with the existing, extensive, forest areas this is also supposedly going to be the marching order in the future too (Zakeri, Syri & Rinne, 2015). However, several limiting factors for biomass use in the future can be identified. First, forests are considered as major carbon sinks. According to EU directives for emissions, Finland must reimburse for the impacts that forest management causes on land use and forestry. This means that, when felling trees, Finland has to plant new trees in order to maintain the current CO_2 binding capacity. Furthermore, the harvesting must not be too extensive. Further, the wood that is produced as a by-product might not be enough to sustainably satisfy the ambitious targets of biofuel use, that the Finnish government has set out. At actualisation, this could require Finland to consider biofuel imports, which would go against the targets set out in the first place (IEA, 2018).

4.2.4.1. Forest biomass

Approximating the potential share of forest biomass in the future electricity generation is not an easy task. Even though there are existing studies, results vary vastly depending on the different geographical focus areas, research approaches, applied constraints and limitations, made assumptions as well as type of biomass used (Zakeri, Syri & Rinne, 2015). Taking the current sustainability specifications into account, a total potential of nearly 107 TWh in annual capacity of bioenergy from the Finnish forests has been estimated (Sikkemaa et al., 2014). However, biomass is a main alternative for coal and, thus, will be used as support to replace coal during the phase-out of coal as well as a substitute for oil in district heating (IEA, 2018). The total coal capacity, all energy and electricity generation, that will be replaced before May 2029 is 31 TWh (statistics from 2018) (Statistics Finland, 2019). This means that the maximum capacity on forest biomass available for electricity generation is just a fraction of the maximum potential.

The existing peat capacity is also to be partly replaced due to the government programme which states current peat usage should be cut in half by 2030 (Finnish Government, 2019). The main substitute for peat is wood-based fuels as several of the power plants which use wood fuels as primary fuel, also use peat as a complementary fuel in the process. This is mainly since peat has a fixed price and high availability in the current system. It is also stated that the peat price acts as a target price for wood fuels. This means the price of peat, is the highest price, that plants are prepared to pay for wood fuels. In case the price is higher, thy will just use more peat, or even all peat, instead (Arasto, Kujanpää, Mäkinen, Zwart, Kiel & Vehlow, 2012). The amount of peat that is used in the current energy system is 19 TWh (statistics from 2018) (Statistics Finland, 2019), of which 3.3 TWh is used in electricity generation (Statistics Finland, 2019). Since this thesis will examine a 100% renewable electricity generation, this 3.3 TWh share will be replaced by wood fuels as well as 6.3 TWh of other uses, replacing a total of 9.5 TWh of peat. This decrease of 9.5 TWh in peat is in accordance with the goal by the Finnish Government to cut peat usage in half by 2030.

When taking these replacement requirements into account, the total capacity of biomass that has to be prioritised to other uses, is 40.5 TWh. When the current forest biomass utilisation of 57 TWh, 40 TWh of biomass for power and heat generation and 17 TWh of biomass for small-scale housing in 2018 (Statistics Finland, 2019), is added to this, the total amount of forest biomass demand in 2030 will be 97.5 TWh. This would mean a lot of the 107 TWh of sustainable capacity demonstrated by Sikkemaa et al. (2013) would be required to compensate for the phase out of coal and partial replacement of peat in the energy system. For this thesis, this means the biomass potential will be increased with the potential 9.5 TWh and the substituting of the existing shares of coal and peat, in 2018 5.4 TWh and 3.3 TWh respectively (Statistics Finland, 2019).

4.2.4.2. Biomass from waste and agricultural biomass

Without a low rate of unused potential in the forest biomass, there is other types of biomass that might be of greater importance in the future. There are some studies that have approached the bioenergy potential in different kinds of waste (Höhn, Lehtonen, Rasi & Rintala, 2014; Peura & Hyttinen, 2011) as well as bioenergy that originates from agricultural farming activities (Mikkola, 2012). However, these usually include the same kind of biomass, so in order to not duplicate any effect, they are both included in the same section here. The products included in these two categories are both municipal and industrial biowaste, different kinds of sludge, farming residues, i.e. the straws from the cereal, crops that are specifically farmed for energy generation as well as other agricultural waste and by-products, like livestock manure. This kind of biomass is usually transformed to biogas. Biogas can be used in transport, but a more traditional application is to use it as a substitute for natural gas in gas power plants (Mikkola, 2012). Biogas is formed through a complex reaction of CH_4, from the composting process of the waste, and atmospheric CO_2. The population and economic structure of the area dictates the type of biomass that can be used to produce the needed CH_4. In big cities with a lot of people, there is great amounts of biowaste too. On the contrary, agricultural areas have more field biomass and livestock manure (Höhn et al., 2014).

The potential in these waste products is significant, but at the same time this is an almost untouched area when it comes to energy generation. Mikkola (2012) approximates the possible utilisable annual capacity as 12 – 22 TWh, of which only 0.5 TWh is being utilised. The gap of 10 TWh in the potential depends on the extent to which unused croplands are utilised for growing energycrops, like canary grass. The lower value indicates farming of energycrops on an area of 100.000 ha (1,000 km^2), while the higher value represents the possibility when energycrops are farmed on an area five times greater, 500,000 ha (Mikkola, 2012). This would mean an energy density of 2.5 TWh per 100,000 ha of farming land used.

Since farming has historically been mainly based on growing food and fibres to meet the basic needs of the society, the traditional farming and the growing of energycrops compete for the same farming areas (Harvey & Pilgrim, 2011). However, none of the existing farming should be replaced by the farming of energycrops. Finland had 246,300 ha of set-aside land in 2018 (Statistics Finland, 2019), that could have been used for farming of energycrops without affecting the rest of the agricultural activities. The European Commission allows other arable crops than food crops to be farmed on set-aside land, which means such additional farming is possible (Regulation (EU) No 1307/2013).

Höhn et al. (2014) examined the maximum production of biogas in three municipalities in Southern Finland, while, Peura and Hyttinen (2011) assessed the biogas potential in South Ostrobotnia. For the municipalities in Southern Finland, the potential energy amount was estimated to be 2.8 TWh. This number included all different kinds of waste, biowaste, agricultural residues and energycrops (Höhn et al., 2014). For South Ostrobothnia the same number was 2.2 TWh (Peura & Hyttinen, 2011). These results are assumed to be generalisable for the whole country, just by studying the population density in the researched areas, similar to Zakeri, Syri and Rinne (2015). The total population of Finland is approximately 5.5 million inhabitants (Statistics Finland, 2019). The Finnish population is still increasing and therefore will be even higher in 2030. The population has increased with a rate of 18.7 thousand persons annually, 5.181 million in 2000 and 5.5 million in 2019 (Statistics Finland, 2019). For 2030 this would mean 5.7 million inhabitants. Höhn et al. (2014) reports the population in the studied areas as 585,700 inhabitants, while Peura and Hyttinen (2011) reported a population of 538,975 inhabitants. Scaled up to match the total Finnish population in 2030, the total potential of biomass would be 27.5 TWh and 23.4 TWh in the two studies respectively. These numbers are similar to the upper limit presented by Mikkola (2012). Taking the set-aside land and the research of Mikkola (2012) into account, the result is an annual potential of 15.7 TWh from agricultural residues (9.5 TWh) and farming of energycrops (6.2 TWh). This 15.7 TWh will be considered as the maximum potential for other than forest-based biomass in 2030.

4.2.5. Summary of the possibilities for RES in 2030

Even though Finland already has a considerable share of RES integrated into the electricity system, there is a lot of room for further improvements until 2030. Table 3 below summarises the findings in the sections 4.2.1 through 4.2.4.

Table 3. Summary of renewable electricity generation capacities for 2018 and 2030

RES	**Generation capacity 2018 [TWh/a]**	**Generation potential 2030 [TWh/a]**	**Potential increase [TWh/a]**
Solar PV	0.1	6.0	5.9
Wind power	5.8	24.0	18.2
Hydropower	14.0 *	14.0	0.0 †
Biomass	12.1	45.5	33.4
forest biomass	11.6	29.8 ‡	18.2
waste, farming	0.5	15.7	15.2
Total	**32.0**	**89.5**	**57.5**

* Average from 2009 – 2018 considered as capacity. Generation in 2018 was 13.1 TWh.

† No added capacity for 2030 could be identified

‡ Replaces all coal and peat in current system and increases by 9.5 TWh

The potential increase in generation capacity is sizeable, almost three times bigger than the capacity in 2018. The potential increase is greatest in the solar PV, which would according to these assumptions have the potential to grow with a factor of sixty. Nevertheless, the solar power capacity that is installed at the moment is so small that even after this increase solar PV is still about the same size as wind power already is today. Wind power would have the potential to quadruple in capacity, while hydropower remains the same as it already is. Hydropower generation in 2018 was less than the ten-year average, 13.1 TWh compared to 14 TWh, but still the average value is considered as the existing generation capacity. Biomass showed a great potential for growth. However, a substantial part of the potential will be used to substitute coal, due to the phase-out, and some peat in accordance with the targets of the Finnish government. This means some of the forest biomass will be used in heat production too, even if not regarded in this thesis. Even though these replacements of other fuels, forest biomass still has a remaining growth potential. Further, biomass from waste and farming shows great possibilities too, as this share remains almost untouched at the moment.

4.3. Energy storage possibilities

In order to increase the amount of RES that are used in Finland, the utilised energy storage capacity should also be increased. This is due to that in an energy system which is based on high shares of renewable energy, the need for energy storage solutions on a daily, weekly and seasonal basis are a prerequisite (Child & Breyer, 2016a). An energy system with high shares of RES calls for energy storage solution as a part of the electricity system. Zakeri, Syri and Rinne (2015) argue that the Finnish electricity system could cope a RES share of 69 – 72% of gross total production, without considerable changes to the system. However, since the share is higher, a higher flexibility will also be required.

4.3.1. PHES

Even though hydropower generally is available throughout the year, hydropower also has a seasonal aspect in Finland. Consequentially hydropower is also used as an energy storage in the Finnish energy system (Child & Breyer, 2016a). Even though this provides additional flexibility, this is not considered as PHES, but instead as flexible hydropower (Sharma & Singh, 2013). Since all the available natural hydropower locations are already utilised, artificial reservoirs are a possibility for the future PHES in Finland. However, the expenses of building a new site are severe, it is worth to consider if some existing site can be converted to serve as PHES. For instance, the former mine in Pyhäsalmi is planned to be transferred into an underground PHES. The planned storage capacity is 75 MWh, with the possibility to expand with parallel units in the future (Laatikainen, 2016). At realisation the falling height would be a record setting 1,400 meters. The initially planned maximum output is 200 MW. Since the height is sizeable, the required water masses would be relatively small. This project is planned to start in 2019 (Talouselämä, 2013). Apart from Pyhäsalmi, Finland has several abandoned mines, some of which could supposedly be converted to PHES in the future (Kivinen, 2017).

4.3.2. CAES

CAES is a known technology, but at the moment there are only two large scale CAES plants in the world, one in Germany and one in the United States. This could be due to the unique requirements the technology has on the geology (Johnson et al., 2019).

However, Finland has a stable bedrock, resulting in good possibilities for CAES. For instance, Sipilä, Wistbacka and Väätäinen (1994), described in their study that CAES can be utilised in old mines. Even though there have been studies on the possibilities of building a CAES in Pyhäsalmi (Sipilä, Wistbacka & Väätäinen, 1993), the same mine as discussed in PHES, these two storage technologies do not compete of the same capacity. While PHES as a technology can use open-cast mines and quarries, CAES requires a closed space in order to build up the required pressure. Rock which is dense and airtight enough is usually found deep in mines, in caverns and smaller spaces (Sipilä, Wistbacka & Väätäinen, 1994). Since the requirements for the mines are different, these two storage technologies do not compete of the same capacity, even though they can be built using the same mine. For Pyhäsalmi, a 30,000 m^3 cavern was calculated to have the storage capacity of 210 MWh and maximum output capacity of 34 MW (Sipilä, Wistbacka & Väätäinen, 1993). Since Finland has a stable bedrock and abandoned mines, the total utilisable capacity will be considerably larger than the storage capacity this one facility could alone provide.

4.3.3. Flywheels

Flywheels are a mature storage technology, that has the capacity to grant short duration support to the grid, mainly concerning the power quality. Thus, flywheels can be used to stabilise the output from wind power and provide grid stabilisation when changing between energy sources (Lund et al., 2015). However, flywheels do not present cost-effective alternatives for load-shifting applications in a bigger scale and cannot be considered as a suitable solution for long term energy storage (Zakeri & Syri, 2015).

4.3.4. TES

TES can be used either for heat and cooling applications or as energy storage that is converted to electricity when the electricity system requires (Begeal & Decker, 2011). The storage media can either be with or without phase changes, sensible of latent. According to Hauer (2013), sensible heat storage with water has a total storage capacity 10 – 50 kWh per tonne of storage media, and the power output can be up to 10 MW. Latent heat storage and PCM, on the other hand, allows higher capacities, 50 – 150 kWh per tonne of storage media, but the power outputs are lower, only 1 MW. From these numbers it is clear that TES are not that good for short term storage with rapid changes, but instead they could serve as seasonal storage, where the changes are slower and less variable.

In Finland Helen is a company which has several ongoing projects for thermal storage in Helsinki area. For instance, a 260,000 m^3 water cistern in Mustikkamaa is planned to commission in 2021 (Helen, 2018b) and 300,000 m^3 rock caverns are planned to function as seasonal thermal storage in Kruunuvuori starting from 2030 (Helen, 2018a). The first mentioned project is an energy storage that can be used to balance the electricity grid, but the latter one is only suitable for thermal applications, which means that even if it will lower the overall heating and cooling costs as well as energy consumption related to them, the scope of this thesis is limited to energy storage that can be used for grid balancing. The water cistern in Mustikkamaa is planned to have a total storage capacity of 11.6 GWh, with a power output of 120 MW. This 11.6 GWh capacity translates to an energy density of 45 kWh/tonne, which is in line with the numbers by Hauer (2013).

4.3.5. P2G and P2H

In P2G and P2H energy is used to synthesise gas and hydrogen respectively. The SNG that is generated in P2G can be directly used in conventional gas power plants. Finland has, by 2019, 2,900 MW of power plants with some kind of gas as primarily or secondary fuel (Energy authority, 2019). This means Finland already has almost 3,000 MW of capacity to use for transferring the stored energy back to electricity. Hydrogen on the other hand, could be used in fuel cells. At the moment, the problems with fuel cells are the low availability and relatively high prices. However, in the future both these issues are assumed to be fixed (Sørensen & Spazzafumo, 2018). Further, since the stored gas can be used in existing gas operated power plants, which have proven to have the needed power output to serve in the current electricity system, this thesis assumes the power output will be sufficient in a future energy system too.

The main problem with P2G and P2H is the low efficiency that the two technologies have. Still, even though the efficiencies are lower than in some other available technologies, the storage capacity is very big. This is due to an abundant availability of reactants, water and CO_2, and a great amount of storage media. The synthesised gas can be stored in the existing natural gas pipelines, which means that most countries already have significant energy storage networks built, and if the fossil energy generation is decreasing, the gas pipes will become redundant if there is no other use for them. Currently, the length of the main piping in the gas grid is 1,150 km and the pipe sizes differ between DN100 and DN1000 (Gasgrid, 2019). According to the ISO standard (6708:1995), the DN pipe sizes are dimensionless whole numbers which are "indirectly related to the physical size, in millimetres, of the bore or outside diameter of the end connections" (p. 2). This means the outside diameter of the pipe is bigger and the inside diameter is smaller than the DN size indicates. Since the pipe wall thicknesses are not available, the actual inner diameter cannot be calculated. This thesis assumes the average inner diameter of the pipes in the gas grid is between the two pipe sizes, at 450 millimetres. This gives the Finnish gas grid a total volume of 183,000 m^3, excluding the storage tanks spread around the country. The lowest operating pressure in the piping is 54 bar (Energy authority, 2018). With a volume this big, and pressure this high, the total amount of SNG that can be stored in the gas network piping is approximately 9,750,000 m^3, when not taking the compressibility into account. The heating value of SNG depends on the amount of impurities in the gas, the purer the gas, the higher the heating value. Assuming SNG with a relatively low heating value, which is generally used for combustion applications and gas turbines, which has a heating value of 3.5 – 10 MJ/m^3 (Klinghofffer & Castaldi, 2013), the total gas storage capacity would be roughly 9.5 – 27 GWh. As earlier in this thesis, a value in between can be chosen for desired conservativity and correction for made assumptions, namely a storage capacity of 18 GWh.

One operator that might cause a need for further expansion of the gas network is the railroad. Even though the Finnish railway cargo transport was freed for competition in 2007, entering competition has been almost non-existent. However, in 2019 the Estonian state owned Operail announced they will start operations in Finnish railway freight (Heima, 2019). The interesting part is that Operail uses gas powered trains in other areas of their operations in the Baltic (Operail, 2019). It is still unclear if they will operate gas trains on the Finnish railway too, but if they do, it will supposedly boost a future growth in the gas network.

4.3.6. Battery technology

Battery technology has developed significantly in the latest couple of decades, resulting in higher storage capacity and power output per mass. For instance, the traditional lead-acid battery has an energy density of 20 – 40 Wh/kg specific power between 75 and 415 W/kg. More evolutionary battery types like the lithium-ion batteries, that have been vastly used in small appliances, have a specific energy of 90 – 190 Wh/kg and specific power of 500 – 2,000 W/kg (Lund et al., 2015). Due to the high specific energy, a lithium-ion battery of the size of a cube with a side length of 10 meters would have a storage capacity of 400 MWh (Hall & Bain, 2008). The lithium-ion battery also has a low self-discharge rate and high reliability (Lund et al., 2015). The reason the technology is not utilised in practise in bigger applications is mainly due to the high costs that the lithium-ion battery still has (Ferreira et al., 2013).

Lithium-ion batteries are not the only battery type that has proven to have potential, but at the moment the other technologies cannot provide any better solutions either. For instance, the sodium-sulphur battery, which has a specific energy of 100 – 200 Wh/kg and a specific energy between 150 and 250 W/kg (Lund et al., 2015), requires temperatures near 300°C to keep the electrolytes molten in operation (Ferreira et al., 2013; Hall & Bain, 2008). Another high energy density example is the sodium nickel-chloride battery, also called zebra battery. They are light weight and have a fast response time (Ferreira et al., 2013). The specific energy is 85 – 140 Wh/kg and the specific power is 150 – 250 W/kg. However, they are expensive and suffer from high self-discharge rates (Ferreira et al., 2013) and can have the similar temperature requirements as the sodium-sulphur battery (Hall & Bain, 2008).

4.3.7. V2G

As of 2018 Finland had about three million cars (3,021,990) and just short of 110.000 (108,650) vehicles in the heavy transport (Statistics Finland, 2019). Of these cars, the MTC has calculated that in order to be able to have zero emissions in the transport sector in 2045, there should be 670,000 electric cars and 7,000 electric vehicles in the heavy transport in 2030 (MTC, 2018). Calculating the shares of vehicles that have to be replaced by the MTC in order to stay on track for zero emissions in 2045, they are 22% for cars and 6.5% for heavy vehicles. Since the numbers are so ambitious, it goes without saying that a change of this scale will need support from the state to be carried through, namely tax incentives.

As long as the EV that are introduced to the system are PEV, they can be utilised as a mobile energy storage with V2G connections. All the new cars are supposed to be used as V2G storage, while the heavy vehicles are used very frequently and hence no V2G storage is assumed for them. The different battery types available for EV are the same as for batteries in general and the different kinds of future battery technologies are presented in the section above, Battery technology. The electricity consumption in operation varies depending on the vehicle and pattern of use. However, based on the research by Wang, Zhang and Ouyang (2015) an electricity consumption of 18 kWh/100 km can be used as an average consumption for an EV. This means that if it is desired for a car to have the range to drive 400 km, the battery should have an energy storage capacity of 72 kWh. If it is assumed every vehicle would have this capacity, and half of the storage could be used for grid balancing, while the other half would remain untouched for use of the owner of the vehicle as a power reserve, the total V2G storage for the new vehicles for 2030 would equal 24 GWh.

The charging infrastructure in Finland is already partially existing due to the block heaters that are used for prewarming of the engine in the winter. Further, the block heaters have resulted in that Finns are already used to plug in their cars, so the habit of doing so every time they park their vehicle should not be too hard to implement. Even though the electricity grid is already existing, for V2G the grid should allow electricity to move in both directions and it might also be that the low voltage distribution lines and domestic connections do not support the high power transfers the V2G requires (Child & Breyer, 2016a).

5. Calculations

5.1. Calculation program

For the calculations a calculation program was written with MATLAB (2018). The aim of the program was to solve for the different shares of RES that would be needed in a future electricity system to replace the existing fossil fuels, as well as calculate the needed storage capacity. Calculations were made for two different cases, a case where all the electricity generation was done with RES, calculated in section 5.2, and another case where the existing nuclear capacity was included in the total generation capacity, in section 5.3. The two cases will hereafter be referred to as the *all renewable electricity system* and the *carbon-free electricity system* respectively. Since MATLAB is based on numerical calculations, some values and answers were rounded by the program, which led to some values not summing up, depending on the decimals that were rounded. However, this impacted only the first decimal at most, which did not cause any trouble in the rest of the calculations.

In order to get the target values, the hourly energy demand of 2018 was used as a reference and data for the hourly demand was retrieved from Fingrids database (Fingrid, 2019b). In the consumption dataset one hour was missing, January 23 15:00 – 16:00. This was corrected just by interpolating the value from the data of the pervious and next hour. Due to the energy demand in the dataset from 2018 was lower than the estimated demand for 2030, the demand for 2018 was scaled with a factor of 1.1075 so the total demand matched the approximated demand of 2030, i.e. 95 TWh. The consumption data used for the calculations is displayed in graphic form in Figure 1.

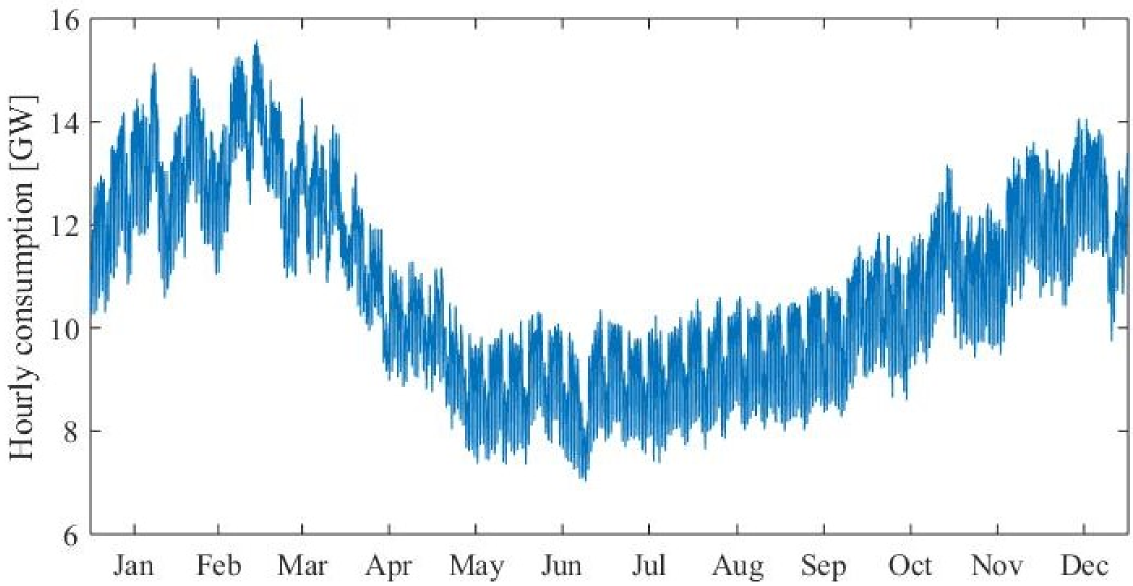

Figure 1. Consumption dataset from 2018 scaled to match the demand of 2030

The data is quite scattered in Figure 1 due to the amount of datapoints, 8,760, but it is clear that the electricity consumption has both seasonal and daily variations. The consumption is significantly greater in the winter months than in the summer, with the highest hourly consumption on February 27, while the lowest values were measured on June 23. In 2018 June 23 happened to be the Midsummer day, which is a main national holiday in Finland. This gives a hint of that the specific dates mentioned related to the consumption data are accurate only for 2018 and, thus, should be understood as indicative. However, in this thesis it is assumed that years are quite similar with just minor variations that eventually will cancel each other.

From the consumption data it can also be seen that the consumption is higher in the afternoon every day, regardless the season. At the same time the electricity consumption is at its lowest in the night and early morning throughout the year. Further, worth to note in the consumption pattern is how the consumption changes between the seasons. In Spring the change is very fast compared to the change in Autumn, when the change is more incremental. This could be due to the weather as well as the fact that once constructions and buildings are warm, they tend to store some energy, which translates to lower hating needs, even though the outside temperature would fall. The same logic goes for the Baltic Sea that surrounds Finland on two sides. In spring the Baltic Sea cools down the weather, since it is still cold after the winter. On the contrary, in the autumn the weather is warmer since the sea has been warmed and it has stored energy during the summer.

Solar PV and wind power vary significantly throughout the day, season and year. To account for the variations, the distribution of the energy generation over the year was determined according to hourly data from 2018. The data was retrieved from the database of Fingrid (2019b). The energy generation was scaled, so the total generation was in accordance with the values in Table 3. Both solar PV and wind power datasets are graphically presented in Figure 2.

Both graphs start from zero, but no scale is used in the y-axis since the real generation just depends on a suitable multiplier which is applied to all values. This means the relation between the values in a dataset values stay the same regardless to the chosen multiplier. A first observation in the solar PV data is that it looks filled due to the heavy hourly variations. The data shows that solar PV is generally zero every day at night, with only a few exceptions with electricity generation through the night during the summer months, which is shown by lighter area at the bottom part of the graph, mainly in June and July. Also, solar PV shows a clear seasonal aspect, with greater generation in the summer and lesser, at times almost negligible, generation during the winter months. Wind power on the other hand has also hourly and daily variations, but the variations are not regular or seasonal in any aspect. The generation is mostly greater during the night, but otherwise the wind profile stays quite similar throughout the year.

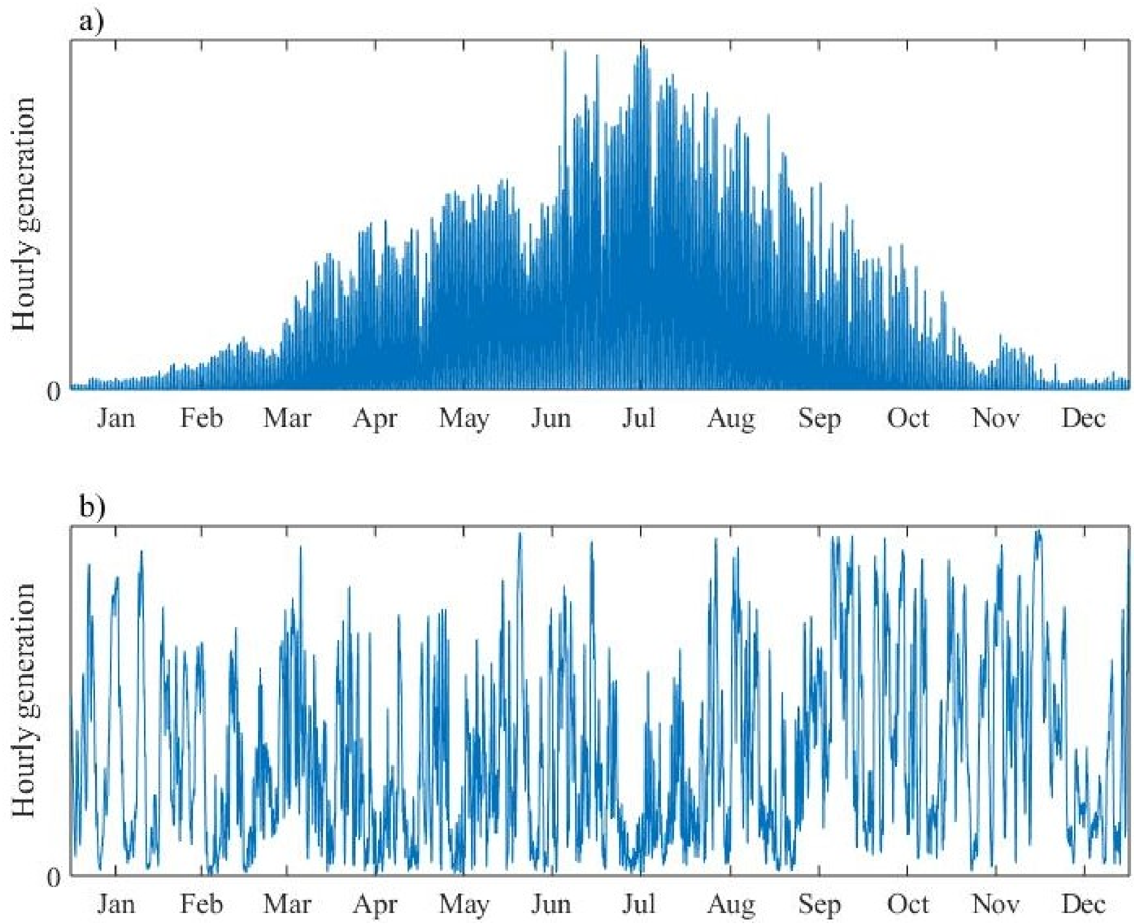

Figure 2. Power generation profile for a) solar PV and b) wind power

Hydropower is generally quite stable, which means the generation is evenly distributed over the year. However, now it was given a flexible share of 40%. This means that the generation was otherwise evenly distributed over every hour of the year, but 40% of the capacity was given the flexibility to be tapped whenever needed. This flexible share represents the generation that is not done with run-off hydropower and can be regulated. The 40% equals 5.6 TWh in annual capacity, leaving the static capacity at 8.4 TWh. Power generation from forest biomass was assumed to be divided evenly over the year, while the waste and agricultural biomass had a flexibility equal to the share of the farmed energycrops, 6.2 TWh. This means that the biomass originating from waste was assumed to be evenly distributed over the year, while energycrops were allowed to be harvested and used whenever needed. The static share of biomass totalled at 39.3 TWh in annual generation. Consequentially, the total annual flexible energy capacity, from hydropower and energycrops, in the calculations was 11.8 TWh.

The calculations were based on a case where Finland is not selling any energy to the electricity market, but instead all the excess energy is stored. Storage capacity was calculated as the sum of all points when the supply was greater than the demand. Storage was not allowed any negative values, but it was allowed to go to zero. The maximum value in the cumulative energy storage was considered the momentary maximum storage capacity that is needed in TWh. The charging rate and discard rate of the energy storage were examined as the biggest increase and decrease in stored energy during an hour. This value was then regarded as the maximum required capacity for continuous power input and output (in GWh/h, or simplified just GW). The energy storage was given an efficiency of 0.7 for the double cycle, i.e. only 70% of the electricity put to storage could be transferred back to electricity and used when needed. Worth to note is that the efficiency was applicable only for the electricity that was stored, not the flexible generation. The flexible generation was calculated without additional losses.

5.2. The all renewable electricity system of Finland 2030

As summarised in Table 3, the maximum potential of electricity generation capacity from the different RES is calculated to 89.5 TWh in 2030. Considering the estimated total electricity demand of 95 TWh for 2030 implicates that the Finnish electricity system cannot be self-sufficient *and* 100% renewable in 2030 yet. Since the renewable capacity will not be enough to cover for the whole demand, no optimisation of energy source distribution will be possible to carry out in this case. However, in order to be able to later compare the two cases, the total amount of required energy storage was calculated. Figure 3 shows the estimated consumption and the full utilisation of the generation with RES, excluding the 11.8 TWh of flexible generation.

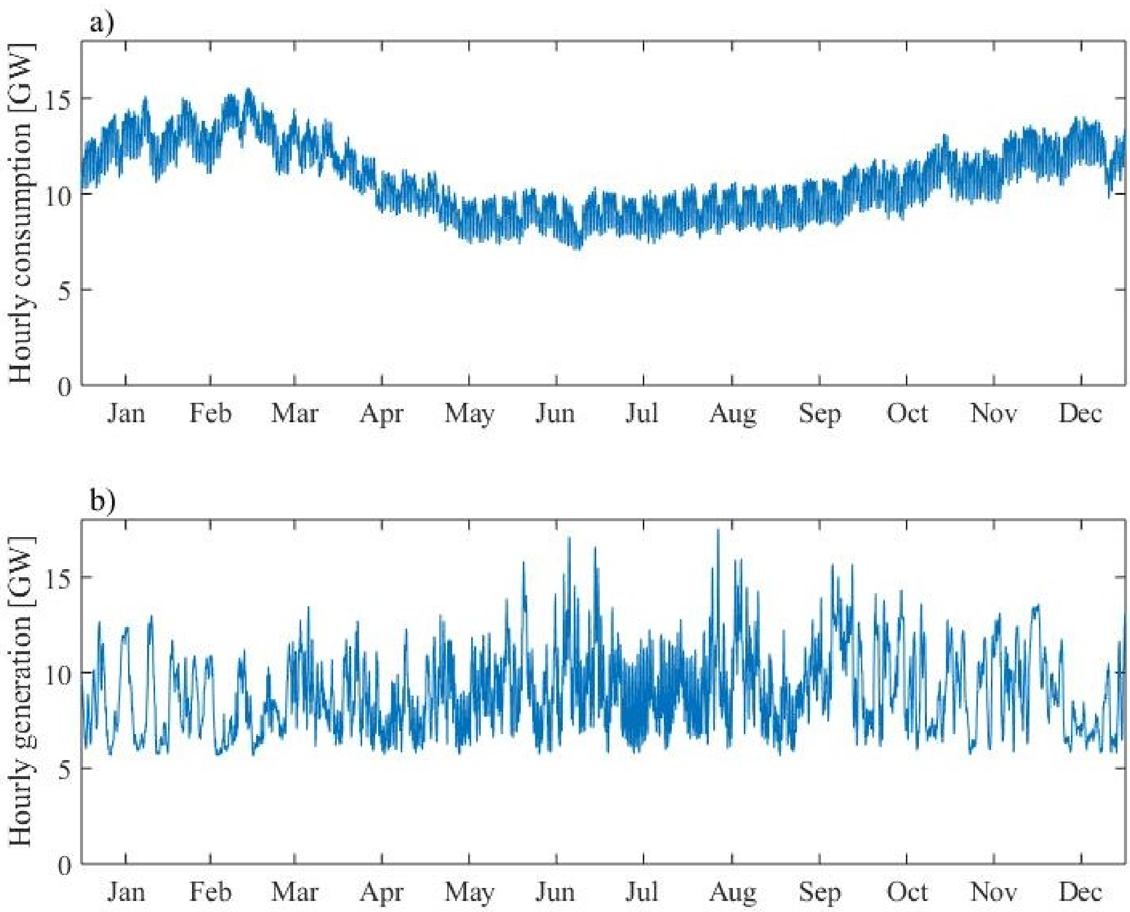

Figure 3. a) Power consumption and b) RES generation

As the graphs show, the consumption and the generation do not match. The generation is fairly similar throughout the year with significant hourly variations, while the demand is more static and with clear seasonal variations and predictable hourly variations. Since the flexible generation is not included in the graphs, it can be used whenever the momentary generation or electricity from storage cannot cover the demand.

According to the calculations, just over 26% of the time the RES electricity generation was higher than the electricity demand. This was calculated using hourly measures, which means the generation was higher for 2,314 hours of a total of 8,760 hours. The hours with a higher electricity generation than demand, occurred mainly during the summer months, when the generation from solar PV was at its highest and the demand at its seasonal lowest. During the times with a greater supply, a total of 4.0 TWh worth of electricity was stored. This was just about five percent of the electricity that was generated when excluding the share of generation that is considered as flexible, namely the flexible part of hydropower and the energycrops. However, the cumulative maximum, the highest value when the storage is allowed to build up, was only a fourth of the total share that was put into storage during the year, 1.0 TWh of the total 4.0 TWh. This was due to the stored electricity was generally consumed only in a matter of hours or at most days. The maximum charging capacity was calculated to 8.2 GW, while the discharge rate resulted in 7.1 GW. The cumulative storage maximum occurred at the end of the summer, on August 25, when the consumption had been low for several months at the same time as the solar PV had been relatively high.

Since the all renewable energy generation was not enough to provide Finland with the electricity that was demanded, the rest of the required electricity would have to be bought from the electricity market or produced with other means. However, due to how the calculations were conducted, the remaining demand was very variable. In order to meet this variable demand, the best alternatives for generation would be the existing peaking plants. However, the main problem with the peaking plant, is that they are run with natural gas and consequentially the electricity generation would no longer be 100% renewable. Also, if the peaking plants are already included in the storage systems, like P2G, it might be they cannot be used when needed. In this case with a variable remaining demand, the unsatisfied demand was calculated to be 6.7 TWh. The slight increase in demand, from the difference of 89.5 TWh of supply and 95 TWh of demand, originates from the efficiency of the energy storage.

If the goal was to use a stable, static, energy source to compensate for the unsatisfied demand instead, the calculations should be redone. In this case the storage maximum capacity needed would be 3.2 TWh and this maximum would be reached later in the year, in the middle of October, October 14 Also, both the maximum calculated charging capacity and discharge rate would be 8.9 GW. The remaining demand would increase too, from 6.7 TWh to 7.3 TWh. This demand divided evenly over the year would result in a remaining hourly demand of 831 MW. This, evenly distributed demand, case will not be further continued, but was included as illustration of different possibilities.

5.3. The carbon-free electricity system of Finland 2030

According to the current outlooks for 2030, Finland will have three nuclear reactors in Olkiluoto, two reactors with 890 MW capacity and one with 1600 MW. Calculating with the same efficiency as the current system, 0.89, the total annual generation would be approximately 26.4 TWh. Adding this to the potential electricity generation with RES, a total of 115.9 TWh would be reached in 2030. In this case the total generation capacity exceeds the demand, and an optimisation of the generation capacity allocation can be performed. According to the literature, energy storage solutions are an expensive investment in renewable energy systems (Zakeri & Syri, 2015), thus, the target for the optimisation was set to minimise the need for storage capacity, i.e. minimise the highest value in the cumulative storage. Further, since the actual costs of the different RES depend on the state involvement and politics, these are very hard, if not impossible to estimate. This means an optimisation for the lowest overall cost for the system would be an equally hopeless task.

First, all the already existing capacity, both nuclear and RES, will be utilized to 100%. This means the minimum values for the different energy sources are the ones stated as existing capacity for 2018 in Table 3. This means none of the existing energy generation facilities will be replaced, but instead maintained when needed. Maintenance is supposedly much cheaper than the building of new plants and, thus, the investment costs in new capacity are minimised. Since the nuclear reactors are existing, they will be run at full capacity, i.e. 26.4 TWh evenly distributed over the year. For the rest of the electricity generation sources, same generation profiles as earlier were supposed. However, they were scaled according to the results from the optimisation. The optimisation was carried out with regard to minimise the cumulative storage, i.e. the required storage capacity. Also, the calculations were conducted with the assumption that no excess energy, or electricity that will not be used in the Finnish system, will not be generated. This means all of the generated energy will be used, either immediately or from storage at a later time.

When the nuclear capacity was introduced to the energy system, the total renewable generation potential was not to be utilised to 100% anymore. The existing RES generation and shares of the different generation types were calculated as a minimum. To this minimum, the potential increments were calculated as the maximum potential subtracted by the existing capacity. The shares of increased generation and the total increase in capacity for the different RES were calculated and results can be seen in Table 4 below. The share of hydropower is not included in the table, since no potential increase could be identified earlier in the thesis.

Table 4. Fractions of potential and sums for RES in the carbon-free electricity system

RES	**Potential increase 2030 [TWh/a]**	**Fraction of utilised potential 2030**	**Total increase 2030 [TWh/a]**
Solar PV	5.9	0.0	0.0
Wind power	18.2	0.42	7.6
Biomass	27.2 *	0.89	24.0
Total	**51.3**	**0.62**	**31.6**

* Biomass potential does not include share of energycrops, 6.2 TWh

As it can be seen in Table 4, the potential increase of the most variable of the RES considered, solar PV, will not be utilised at all. This is due to the high variability of solar PV results in major swings in the energy storage. The other variable RES potential, wind power, would utilise 42% of the potential increase. This equals an annual generation increase by 7.6 TWh. The potential increase of the biomass capacity does not include the flexible share provided by energycrops. This is due to the most feasible case is to take full advantage of the full flexibility provided by the energycrops. Since both, forest-based biomass and biomass from waste and farming (when energycrops are excluded), are assumed to be static, or evenly divided over the year, it does not matter how the capacity is divided between these two. The only thing that matter is that the total increase in capacity should be 24.0 TWh of the potential 27.2 TWh, which translates to 89%. The combined capacity equals a total utilisation of the increase potential of 62%. A total of 31.6 TWh increase in the non-flexible RES capacity is required in for 2030. Further, 6.2 TWh of new flexible generation is required, which translates to a total RES increase by 37.8 TWh in annual generation. Compared to the maximum potential of increase in RES from Table 3, the total utilisation rate is 66%.

With the information from Table 3 and Table 4, the total RES generation was calculated to be 69.8 TWh for 2030. Of this capacity, 11.8 TWh was totally flexible generation, partially from hydropower and from the farmed energycrops, 44.5 TWh was static generation evenly distributed over the year, namely most of the hydropower and energy from biomass excluding the energycrops, and the rest, 13.5 TWh, originates mainly from wind power since the solar PV contribution was almost negligible, only 0.1 TWh. Summary of the total generation capacities for 2030 are presented in Table 5. The total capacity of 2030, 69.8 TWh, means that nearly 78% of the total RES potential of 89.5 TWh would have to be utilised in 2030.

Table 5. Electricity generation in the carbon-free electricity system

RES	**Generation capacity 2018 [TWh/a]**	**Capacity increase [TWh/a]**	**Total capacity 2030 [TWh/a]**
Nuclear power	21.9	4.5	26.4
Solar PV	0.1	0.0	0.1
Wind power	5.8	7.6	13.4
Hydropower	14.0 *	0	14.0 †
Biomass	12.1	30.2	42.3 ‡
Total	**53.9**	**42.3**	**96.2**

* Average from 2009 – 2018 considered as capacity. Generation in 2018 was 13.1 TWh.

† Includes both the static and flexible generation, 8.4 and 5.6 TWh respectively

‡ Includes both the static and flexible generation, 36.1 and 6.2 TWh respectively

In the carbon-free electricity generation, i.e. the combined nuclear and RES generation, the supply was greater than the demand for 2,554 hours out of 8,760, which translates to 29% of the year. The hours with a greater generation occurred during the summer. Since the times with a higher generation than demand were limited to only a few occasions, mainly in the summer, the impact of a low consumption is emphasised. At the same time, due to the low utilisation of solar PV, the remarkable storage requirement solar PV as energy source has, is emphasised. The hours with a greater supply resulted in a total of 3.2 TWh of electricity that was to be stored. When comparing this 3.2 TWh to the total generation, excluding the flexible energy generation, originating from the flexible share of hydropower and the energy generation based on energycrops, the share equals 3.8%.

If it instead is compared to only the renewable electricity generation the share that is stored is slightly higher, 5.6%, this also excluding the flexible generation. The graphs for the consumption and electricity generation, excluding the flexible generation, are shown in Figure 4.

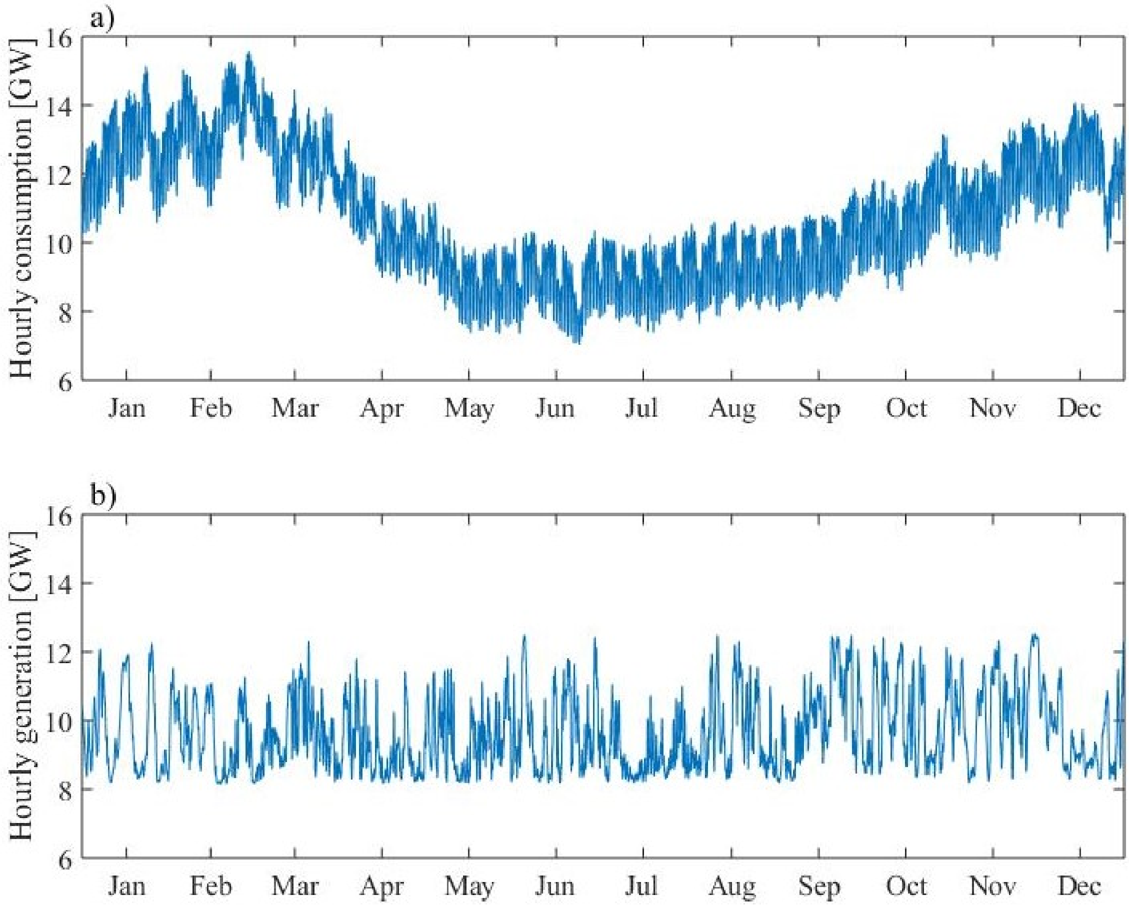

Figure 4. a) Power consumption and b) electricity generation

As the graphs show, the consumption and the generation still does not match. However, the generation is quite stable, and the variations are much more subtle than before. This is because of the amount of the static, evenly distributed generation, is significantly larger when compared to the other types. The flexible generation is not included in the graphs. This means that when the demand is higher and there is no energy in store, the flexible generation can be utilised. The maximum charging rate of the storage was calculated to 4.4 GW, while the highest discharge rate was 5.5 GW. The total cumulative maximum for the storage totalled at 1.4 TWh and since the generation was optimised, the energy was consumed quite slowly and the storage maximum was reached at the end of September, on September 29 according to this specific dataset from 2018.

As stated earlier, the calculations were based on the idea that Finland would not export any electricity or sell to the market, but instead be self-sufficient when it comes to electricity. This means also no electricity will be bought from the electricity market. The total annual generation, including both the generation with nuclear power and RES, was 96.2 TWh, only 1.2 TWh over the total demand. This difference originates from the efficiency of the storage cycle.

5.4. Results

Of the two cases calculated, the all renewable electricity system and the carbon-free electricity system, the first one is considered as a comparison or baseline, while the latter one is the system that will be object for further analysis. This is due to the fact that generation with only RES is not able to provide Finland with the estimated electricity demand in 2030, which means the all renewable system fails to meet the demand. At the same time the existing nuclear capacity resulted in that the carbon-free system based on the generation potentials is able to do it. The intention of the calculations was to minimise the needed storage capacity. The solutions are not claimed to result in the minimum overall system costs, even though the already existing capacity is taken into account. Naturally, this will discount the costs related to building new generation capacity, but in an electricity system the total expenses are more complex than the calculations allow. The main reason for the optimisation not aiming to minimise the overall system costs, is the severe impact that state involvement and politics play on the cost of the different RES and storage solutions. Namely, if the government promotes only one kind of electricity generation or energy storage technology, the chances are that the selected technology will cheapen. This makes optimisation for the overall cheapest solution impossible when not knowing the future direction of politics.

In the carbon-free electricity generation, the supply was greater than the demand for a very similar time as in the all renewable system, 2,554 hours compared to 2,314 hours out of 8,760 hours in total, and in both cases the hours with a greater demand occurred mainly at the same hours. Since the times with a higher generation than demand were limited to only a few occasions, mainly in the summer, the impact of a low consumption is emphasised. At the same time, the low utilisation rate of solar PV in the carbon-free system underlines the significant energy storage demand that solar PV sets on the electricity system. Even with almost no solar PV whatsoever, the generation pattern fluctuated less when compared to the one of the all renewable system, which had significantly more generation with solar PV. Solar PV is highly variable and when no excess generation is allowed, the storage need outgrows the benefits.

When comparing Figure 3 and Figure 4, it is clear that neither of the generation graphs b) match the consumption graph a). However, the generation is more stable in the carbon-free system which leads to a smaller amount of energy that has to be stored. This is completely due to the optimisation aspect of the carbon-free case. The hours with a greater supply resulted in a total of 4.0 TWh of electricity that was to be stored in the all renewable system, while it was almost a fifth less, 3.3 TWh, in the carbon-free system.

Worth noting is also that even though the total storage was smaller, the cumulative storage was greater in the carbon-free electricity system. The total cumulative maximum for the storage in the carbon-free case totalled at 1.4 TWh, while it was 1.0 TWh in the all renewable case. First thing to remember is that the all renewable system does not have as much electricity in the system, which might explain why the number is lower regardless the optimisation that was conducted in the carbon-free system. This aspect is supported by the lower charging and discharging rates the carbon-free system shows. The maximum charging rate of the storage was calculated to 4.4 GW, while the highest discharge rate was 5.5 GW. These numbers are significantly, 46% and 23% respectively, smaller than in the case with all renewable generation, which means the supply and demand were better balanced in the carbon-free system. Further, the energy was also consumed considerably slower in the carbon-free system. The storage maximum was reached at the end of September, on September 29, which is approximately a month later than the calculations suggested in the all renewable case, August 25. The generation that exceeded the total demand was smaller in the carbon-free system, than in the all renewable system. This can be explained with that the amount of electricity that had to be stored was smaller. Further, even though the carbon-free case had a higher cumulative maximum for storage, the rest of the requirements set on the storage are easier fulfilled and therefore the carbon-free system is more tolerant for different storage solutions. These aspects are entirely due to that the generation was optimised in the carbon-free electricity system.

5.5. Limitations

The calculations presented in the thesis are limited to the input data used, in this case hourly data from 2018. Numbers in consumption and generation will vary from year to year, so the specific solutions demonstrated here are feasible only for the specific data that was used. However, as mentioned earlier, years are expected to be quite similar in the big picture and the minor differences and exceptional conditions are assumed to even out in the long run. Further limitations in the calculations are caused by the use of average values for the solar PV generation instead of actual data from different locations. Finland is very elongated in a longitudinal direction, which means the solar irradiation might be very different in Lapland and Southern Finland at the same time. For instance, during the summer the sun does not set north of the Arctic Circle, while during the winter the sun does not rise in those areas.

All calculations are based on the same level of technology that is available and in use as of 2019. However, in case the technology would take a leap in efficiency the potential increase in generation capacity would naturally grow. Also, the opportunities of new technology are not taken into account. There is always a possibility that in the next decade the clean electricity generation might present earlier unseen possibilities that will revolutionise the field. Further, political decisions and social pressure has the power to shift the estimated energy system in some unexpected direction. When it comes to the energy storage efficiency, the calculations were constructed with an overall storage efficiency of 70%. However, depending on the storage solution that is used this might be too much. In case a smaller value would have been used, the required energy generation would naturally have been higher.

Another aspect that the calculations failed to take into account is the possible shift in consumption pattern that would originate from the electrification of the transport sector. Even though the total consumption has taken into account the estimated increase in the demand caused by more electric vehicles in 2030, the calculations do not take into account that the charging of the vehicles might mainly be concentrated to off-hours, for instance during the night. Since the consumption pattern in the calculations is exactly the same as for 2018, the possibility that the charging of electric vehicles is clustered to similar times is not taken into account. However, when calculated according to the ambitious targets of the MTC (2018), the increase in demand due to electrification of the transport sector is only 2.6 TWh on annual basis, which means the impact should be quite limited.

6. Analysis and discussion

6.1. Selection of method for electricity generation

The different electricity generation sources can namely be divided into three categories depending on their generation pattern: flexible-, static- and variable generation. The flexible generation is generation that can be utilized whenever needed, while the static generation is evenly distributed over the timespan. The variable demand is generation that varies regardless of human activity. For this thesis this means wind and solar PV. All these distinctive generation patterns result together in the total electricity generation. Unless the static generation at most equals the lowest demand and the remaining demand can be covered with fully flexible sources, the electricity system will also need energy storage solutions in order to store the excess energy so it can be used at a later point of time. This is again with the assumption of self-efficiency and that no electricity is allowed to be sold to the electricity market and none is to be bought either.

In the carbon-free electricity system, the energy sources were optimised in order to minimise the storage demand in the system. Solar PV was with support from the calculations deemed as too variable, which is shown in the fact that the optimisation did not suggest increasing the solar PV generation capacity from the current level. At the same time, the wind power, the static generation and the fully flexible generation were all of importance. A significant aspect is that even though more variable generation and static generation would have been accessible, the optimisation resulted in not utilising all of these increase potentials. In other words, the needed storage would increase in case some of the wind power would be replaced by static generation or vice versa. This observation means that the only way to further decrease the storage need in the electricity system is to increase the fully flexible electricity generation. In a sense, the flexible generation is very similar to energy storage and, thus, can cover the same demand.

6.2. Impact of the geographic location on the solar irradiation

Due to the geographical location and the elongated shape of the country, the solar irradiation in different locations can be very different. The earlier data in the calculations was based on a mean value for the country as a whole, so these possible differences are not taken into account. Solar PV was concluded to be insignificant in importance when the objective was to minimise the storage. However, the geographical meaning is now investigated in case plants in different locations would be suitable to even out seasonal variations. In order for solar PV to be fitting for this purpose, the annual irradiation profiles should be as different as possible. The hourly data on the solar irradiation used in Figure 5 is retrieved from the Photovoltaic Geographical Information System (PVGIS) that the European Commission maintains (2019a). Data is selected to represent two opposites in terms of geographical location, Hanko at the southernmost point of mainland Finland and Utsjoki in the northern Lapland. Since Utsjoki is located north of the Arctic Circle, the sun does not set in the summer, but on the contrary, the sun does not rise above the horizon during some of the winter. This provides outstanding possibilities to analyse if the constant sunshine in the summer is enough to compensate for the complete lack of sun in the winter. The data for both places is from the same year, 2016. Since 2016 was a leap year, the datasets have 24 additional hours in February compared to earlier datasets used.

The PVGIS uses a fixed angle for the imaginary area of radiation capture to calculate the values presented in the graphs. Even though fixed, the angles are optimised, so the solar irradiation capture would be as high as possible throughout the year. The angles are measured as the deviation from the horizontal plane, meaning a vertical area would have an angle of 90°. For Hanko the optimal angle is 44° and for Utsjoki, over 1,100 kilometres further in the north, the optimal angle is 54°.

From the comparison of locations in Figure 5 it is clear that different locations do not supplement each other. As it seems, the times with more intensive solar irradiation are very similar and the small differences are not enough to justify having solar PV intentionally in different locations. Instead, a better solution would be to have the solar PV concentrated in the southern parts, since the difference in the amount of annual irradiation is severe. The total irradiation during 2016 in Hanko was over 30% greater than the irradiation in Utsjoki. At the same time the graphs show that the time of sunshine in the summer is longer in the north than in the south and that during June and July the sun does not settle below the horizon. This is simply due to the location north of the Arctic Circle. However, even though the sun shines through the summer nights, the irradiation per square meter is quite low. It can be explained by the fact that the angle the sun can be seen in is very shallow, leaving the irradiation per unit of area very low. Also, even though the sun shines all the time, the irradiation is more intense in the southern parts and, thus, the conclusion that the circumstances for solar PV grow better in Finland the further south the location is.

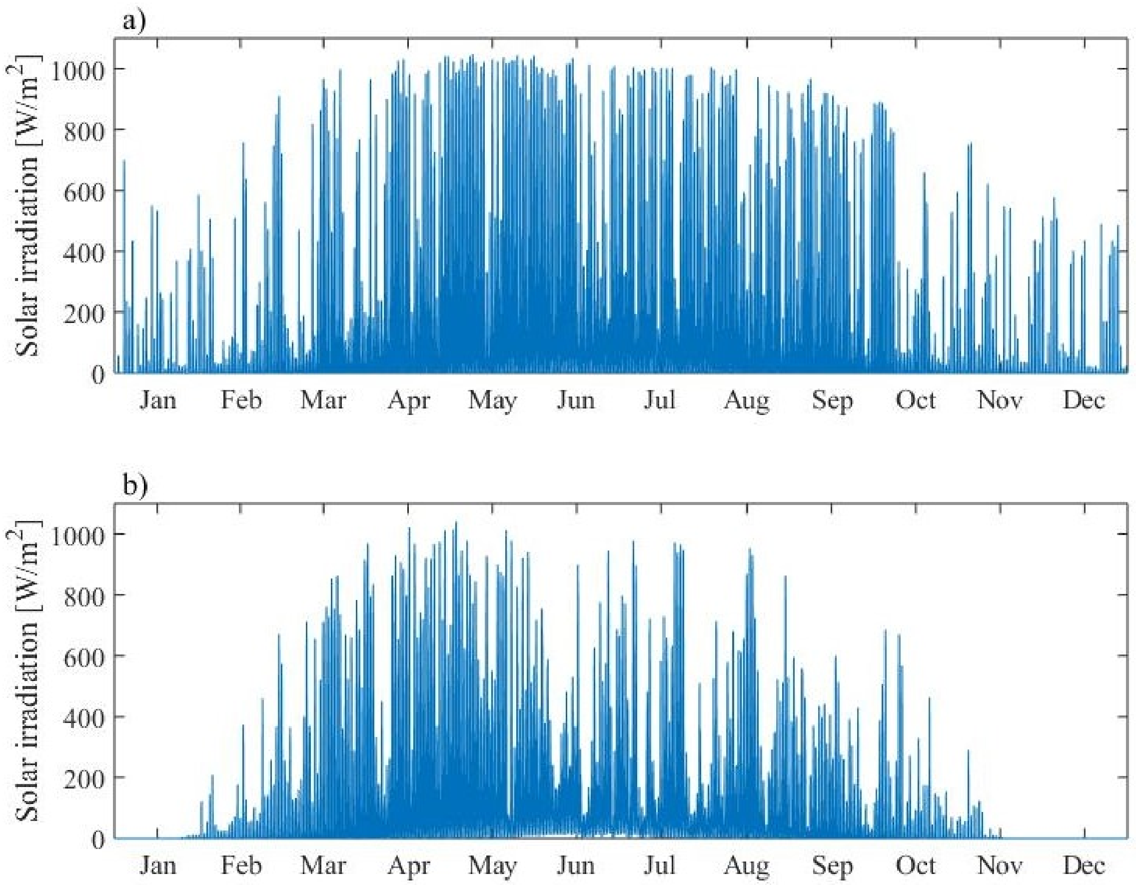

Figure 5. Solar irradiation in a) Hanko and b) Utsjoki

A notable difference between the earlier solar profile, in Figure 2 a), and the one presented here, in Figure 5 above, can be explained by the fact that the data is from different years, 2018 and 2016 respectively, and that Figure 2 is a mean value for Finland as a whole, while Figure 5 represents only two different places. Also, the summer of 2018 was abnormally warm and sunny in Finland (Rinne, 2018), resulting in more evenly distributed and more intense sunshine. Nevertheless, this does not impact the calculations, but it partially explains the observable differences in the different graphs with solar data.

6.3. The emission reduction potential

One of the main incentives for the shift to renewable energy generation in the energy sector, is the emission reduction potential that generation with RES has compared to electricity generation with fossil fuels (IEA, 2019). Regardless the current electricity system, where Finland already utilises RES in the electricity generation, there is still a substantial share of electricity generation done with fossil fuels. As stated earlier, any reduction in the fossil fuels will decrease the total emissions in the electricity system. Worth to note is that even though this thesis mentions the phase out of coal and halving the use of peat until 2030, which also concerns other systems, this section will only consider the potential emission reduction in the electricity system. Since the direct emissions from the usage of RES and nuclear power are equal to zero, the reduction in the direct emissions compared to the current electricity system are in both of the investigated cases equal to the direct emissions in 2018, as stated in Table 2, i.e. 8.29 megatons of CO_2 equivalents. The life cycle emissions, on the other hand, are not as straight forward and must be calculated.

Due to the all renewable electricity system is not enough to provide Finland with the demanded amount of electricity, the remaining demand would need to be generated with non-renewable methods or imported from abroad. This results in that the all renewable case will give a wrong reference and should not be considered too seriously. However, the results from the all renewable case are summarised in Table 6. Since no fossil fuels or nuclear energy is used in this system, they are not included in the table.

Table 6. Life cycle emissions in the all renewable electricity system

Energy source	**All renewable generation 2030 [TWh]**	**Life cycle emissions [Mt CO_2eq]**
Solar PV	6.0	0.29
Wind power	24.0	0.29
Hydropower	14.0	0.34
Biomass	45.5	10.47
Total	**89.5**	**11.38**

The emissions for the all renewable electricity system totalled at 11.38 Mt CO_2equivalents, which is a slight decrease from the life cycle emissions in the current system at 12.75 Mt CO_2equivalents. From Table 6 it is also clear that biomass is a great contributor of emissions compared to the other RES. Even though it is responsible for half of the electricity generation in the all renewable system, the emissions account for over 90% of the total life cycle emissions.

Opposed to the all renewable case, which is not able to provide Finland with the demanded amount of electricity, the carbon-free electricity system, can provide Finland with the electricity that is needed, and hence will be addressed in more depth. The emissions in the carbon-free electricity system are displayed in Table 7.

Table 7. Life cycle emissions in the carbon-free electricity system

Energy source	**Carbon-free generation 2030 [TWh]**	**Life cycle emissions 2030 [Mt CO_2eq]**
Nuclear	26.4	0.32
Solar PV	0.1	0.0 *
Wind power	13.4	0.16
Hydropower	14.0	0.34
Biomass	42.3	9.73
Total	**96.2**	**10.55**

* Value insignificantly small due to negligible generation with solar PV

From Table 7 it can be seen that the total life cycle emissions are smaller than in the all renewable case, 10.55 Mt CO_2equivalents in carbon-free system compared to 11.38 Mt CO_2equivalents in all renewable system. This, even though the generation is 6.7 TWh grater in the carbon-free system. Similar to the all renewable case, biomass accounts for a serious share of generation and the major part of the emissions. In the carbon-free case the biomass contributes with 44% of the total generation, while it is responsible for 92% of the emissions. Regardless this aspect, the emissions are overall significantly lower than in the current system. A comparison of the life cycle emissions in the current system and in the carbon-free system can be seen in Table 8.

Table 8. Comparison of life cycle emissions in the 2018 and 2030 electricity systems

Energy source	**Life cycle emissions 2018 [Mt CO_2eq]**	**Life cycle emissions 2030 [Mt CO_2eq]**	**Change [Mt CO_2eq]**
Oil	0.18	0.00	– 0.18
Gas	2.01	0.00	– 2.01
Coal	4.43	0.00	– 4.43
Peat	2.71	0.00	– 2.71
Nuclear	0.26	0.32	+ 0.05
Solar PV	0.00 *	0.00 *	N/A
Wind power	0.07	0.16	+ 0.09
Hydropower	0.31 †	0.34	+ 0.03
Biomass	2.78	9.73	+ 6.95
Total	**12.75**	**10.55**	**– 2.20**

* Value insignificantly small due to negligible generation with solar PV

† 2018 emissions based on actual generation, 13.1 TWh, not existing capacity, 14 TWh

As the table shows, the carbon-free system would decrease the emissions by 2.20 Mt CO_2equivalents. All the emissions from the fossil fuels are naturally zero, since no generation is done with them. At the same time the emissions from the RES and nuclear power increase due to more generation is done with them, with the exception of solar PV, which remains unchanged. The increase in life cycle emissions is greatest in the generation done with biomass, which is more than three times higher in the 2030 system compared to the current system. Worth to remember is that the current system only represents an electricity generation of 66 TWh, while the carbon-free system represents a generation of 96.2 TWh. This is caused by the fact that the current system has positive net imports of 20 TWh and other sources of generation worth 1.5 TWh, both of which energy source could not be indisputably determined for the emission calculations. When converting the total emissions in Table 8 to emission intensities, the differences are much greater than what the table initially illustrates. The emission intensity in the current system is 0.19 Mt CO_2eq/TWh, while the carbon-free system shows numbers just over half of this, 0.11 Mt CO_2eq/TWh. This means the carbon-free system has a 43% lower emission intensity than the current electricity system. In other words, the switch to renewable energy shows remarkable potential to reduce the emissions associated with electricity generation compared to the current system. Nuclear power has low emissions and should therefore be considered when planning for a system with less emissions. However, the major downside with nuclear power is the radioactive waste that is produced.

Even though the emission reduction potential was already earlier concluded as inadequate to achieve 55% lower GHG emissions than in 1990 on its own, the identified reduction potential remains. Since the emissions baseline in 1990 is 71.3 Mt CO_2eq (Statistics Finland, 2018), a further reduction of 8.29 Mt CO_2eq would mean a reduction of 3.1%. In 2018 Finland had already succeeded to reduce the emissions by 21% from the values of 1990. Since the difference is still so big, 22.3 Mt CO_2eq, the 11.6% contribution by the electricity system is significant. The reason for the share being so small is most probably due to different ways of calculating the emissions. Even though Finland claims to consider the "national totals with indirect CO_2 emissions as the national totals to be used in assessing compliance with the emission reduction commitments under the Kyoto Protocol" (Statistics Finland, 2018, p. 10). Worth to note is the major share that bioenergy contributes to the total emissions, 6.95 Mt CO_2eq. In case the direct emissions are used instead, the total reduction potential is 8.29 Mt CO_2eq, since the direct emissions from RES and nuclear power are equal to zero. This amount equals a reduction of 11.6%, which is considerably higher. However, the potential GHG emission reduction in the electricity system is not enough to help Finland to achieve the government target on its own but should still be regarded as a significant part in the final solution.

An obvious source of error in the values in Table 6 to Table 8, and throughout the thesis, is that the life cycle emissions of both the all renewable and carbon-free electricity system fail to take in to account the impact of the needed energy storage solutions. This means an optimal blend of the different energy sources and required storage technology does exist. However, in order to assess the total lifecycle emissions of the system, including the different storage technologies, more research is needed.

6.4. Future possibilities

The objective of this thesis has been to review the possibilities and limitations a non-fossil electricity system would have in Finland in 2030. In order to do this, several assumptions have been made along the way. However, the assumptions are generally referenced to some articles, let them be academic or non-academic. Still, a decade is a long time and the future is impossible to foretell. For this reason, some aspects have been left out and are not covered in this thesis. This section describes some of the most probable shortages, the reason they are not initially included as well as how they at realisation would impact the results presented in the thesis.

The first major source of error in the thesis is new, more efficient, technology, both in RES and energy storage solutions. For the generation, added efficiency could mean that opposed to the calculations presented, Finland could be self-sufficient and rely fully on renewable electricity generation in 2030. Further, for the carbon-free electricity system this would mean that the potential would be grater, but since neither of the main generation patterns, variable nor static, was fully utilised in the optimisation, the total generation per type would not increase from the values listed in Table 5. This is naturally true only when the same objectives for the optimisation are applied, i.e. to minimise the needed storage. In other words, even though solar PV would take a leap in efficiency, the optimisations would still suggest that none of the potential should be utilised. In case energy storage technology would become more efficient, it would mean that less storage is needed to achieve the required capacity.

In terms of new technology, the current electricity generation technologies that are available and have been covered in this thesis, are mature technologies that have proven in practice. Apart from these technologies, new rising generation methods could not be identified thru all the literature studies conducted for this thesis. Based on this observation, the only electricity generation method that might increase in importance in the Finnish context in the decade to come, is geothermal energy. Geothermal energy is not currently used in Finland for electricity generation (Kallio, 2019), and due to the bedrock in Finland, which only allows for low thermal gradients, the generation of electricity with current technology is not possible (Kukkonen, 2000).

Opposed to the electricity generation, the energy storage technologies are prone to more changes in the near future as various kinds of new technologies seem provide different interesting solutions. For instance, fuel cells seem to make a stand. Fuel cells are electrochemical appliances, which generate electricity through electrochemical reactions. The most intriguing version of fuel cells for energy storage applications are hydrogen fuel cells. This is due to the ease to generate hydrogen through electrolysis and hydrogen is also easy to store in pressurised vessels. In a hydrogen fuel cell hydrogen reacts with atmospheric oxygen and the product in energy and water (Srinivasan, Davé, Murugesamoorthi, Parthasarathy & Appleby, 1993).

Another promising energy storage technology is cryogenic energy storage (CES). In CES electricity is used to cool down air or nitrogen to the point it liquefies. The liquefied gas can be stored at a high density near atmospheric pressures. At peak hours, the liquid gas is heated up by the environment and superheated by external heat sources. The expanding gas is then driven through a turbine to generate electricity (Li et al., 2014). Apart from the cooling of the gas, CES is very similar to CAES. The technology has not yet been proven to work and is still under development. However, CES is expected to have a high energy density and a comparably long storage time. The main problem with CES is most likely the efficiency, which seems to be in the proximity of 40 – 50% (Evans, Strezov & Evans, 2012).

Apart from the current state of generation and storage technology, this thesis assumed for the wind power capacity increase to be limited by the commissioning rate. However, if this assumed limitation is discarded, the all renewable electricity system would benefit, since the total generation could cover the whole demand. When the demand is covered, the first of the RES that would be used for electricity generation that is decreased is the solar PV utilisation. This is completely due to the severe storage need of solar PV that has been discusses priorly in this thesis. However, in the carbon-free electricity all the wind power capacity was not utilised in the current optimisation, so even though the wind power increase would be unlimited in terms of commissioning rate, this would not cause any changes for the carbon-free electricity system.

Another electricity generation source that was object to restricting assumptions is nuclear power. This thesis considered that that the two nuclear reactors in Loviisa would be closed and decommissioned before 2030. Further, the thesis did not include the most recently planned nuclear reactor, Hanhikivi 1, in any way. This means the only nuclear power capacity that was included in the calculations were the two existing reactors in Olkiluoto and the third reactor which is ten years delayed. The operating licences for the two reactors in Loviisa have already been earlier extended and there are no signs of further prolonging them after the expiration date (STUK, 2019). At the same time, the new 1,200 MW nuclear reactor in Hanhikivi is planned to be ready for commercial electricity generation in 2028. However, the reason for this thesis not including this reactor is that the project has not been approved for building yet and the schedule for getting the construction permit is 2021. Further, taking the extensive delays of Olkiluoto 3 into account, the chances for Hanhikivi to start in 2028 are hence considered as very low. Once built the expected lifetime for the reactor is at least 60 years (Fennovoima Ltd., 2018).

If the nuclear reactor in Hanhikivi would after all commission before 2030, according to the current nuclear generation efficiency the annual generation would be 9.4 TWh. For the optimisation in the carbon-free electricity system this would mean less of the other energy sources for static generation would be needed. In other words, the share of hydro power or biomass could be reduced. However, since the hydro power generation cannot be less than in the current system, the only solution is that less electricity from biomass is needed. It does not matter if an electricity generation equal to 9.4 TWh is reduced from the forest biomass or from the biomass that originates from waste, or if the shares of both are reduced. The only constraint for the biomass is that the share of energy crops stays the same as the optimisations initially suggests, i.e. 6.2 TWh.

For the emissions in the electricity system, the completion of Hanhikivi would mean further reductions from the carbon-free electricity system. With the same generation, 96.2 TWh, the total life cycle emissions would go down to 8.50 Mt CO_2equivalents. This is over 4 Mt CO_2equivalents less than in the current system and about 2 Mt CO_2equivalents less than without the electricity generation in Hanhikivi. This is also to show that nuclear power has low emissions and is a preferable energy source when reliable and clean generation is requested. The major downside with nuclear power is the radioactive waste that is left as a residue after the fuel has been used. In Finland the nuclear waste management is quite developed, but Hanhikivi has yet to deliver information to the authorities before a finalised waste management plan can be made (STUK, 2019).

6.5. Impact of increased amount of RES

This thesis has overlooked the technical requirements the increased share of RES would cause on the electricity grid. For instance, an increasing share of RES decreases the ability of the grid to sustain the grid frequency. Traditionally the frequency is maintained by the machines that are connected to the grid, both as supply and demand. The natural inertia in the machines help to stabilise the frequency when the load changes. However, when the generation with RES increases the mechanical inertia decreases and makes the grid more prone to changes in the frequency, which calls for novel solutions for frequency control (Dreidy, Mokhlis & Mekhilef, 2017). This aspect is all too often overlooked in public discussion and should therefore not be forgotten. Without functioning solutions for this issue, increased shares of RES cannot be achieved.

Even though this thesis concentrates on the electricity system, increased shares of RES will also impact other parts of the energy system. For instance, Finland has a substantial amount of combined heat and power (CHP) generation. As much as 21.8 TWh of the electricity generation in 2018 was CHP (Statistics Finland, 2019). In conventional power plants, only a part of the available energy is transformed to electricity and, thus, some of the possible energy remains unutilised. In CHP plants, the part of the fuel that cannot be transformed to electricity is recovered as heat. In this way the total efficiency of the power plants can be increased. The heat is then used in heating applications, like district heating and industry (Statistics Finland, 2019). Since the CHP plants in Finland are mainly run with coal, natural gas and peat (Wilhelms, 2019), a phase out of fossil fuels in the electricity generation will inevitably impact the CHP generation too. Thus, a change in the electricity system will impact the district heating sector and industries as well.

7. Conclusions and summary

This thesis has examined the possibilities for renewable electricity generation in Finland in 2030. Two cases have been examined, one with all renewable generation and one with renewable generation and the existing nuclear capacity. The total potential for RES in 2030 is less than the approximated demand, which means the Finnish electricity system cannot be self-sufficient and totally renewable yet in 2030. When the existing nuclear capacity is included in the electricity generation, the generation is enough to cover the demand. This case shows that the main problem is not to find enough non-fossil electricity generation capacity to cover the demand in Finland, but to maintain the required flexibility. The solution for flexibility that has been covered in this thesis is different energy storage technologies. Different shares and blends of the RES will result in different amounts of energy storage capacity that is needed to preserve the flexibility.

As a solution for the Finnish electricity system for 2030, the generation was optimised with regard to minimising the needed energy storage capacity. Based on the optimisation, solar PV was condemned as too variable with regard to the energy storage capacity. At the same time, wind power, hydropower and bio energy were concluded as important in addition to nuclear power. A carbon-free electricity system like this has great potential of emission reduction. In the solution that minimised the required energy storage capacity, the direct emissions would be reduced by 100%, while the life cycle emissions would be reduced by 17%. In case an additional nuclear reactor would be commissioned, the emissions would further decrease by 20%, to 67% of the emissions in the current system.

From the potential of the different energy storage technologies for 2030, it is easy to come to the conclusion that the energy storage capacity is very limited. Further, the project span is several years at minimum, which means the energy storage capacity should be planned for well ahead. The limited storage capacity also sets some limitations for the electricity generation in 2030. As not one single energy storage technology has the capacity to store significantly more than the others, the energy storage system in the future will most likely consist of a portfolio of several different technologies. As stated earlier in this thesis, Finland is a big country, with a large amount of redundant landmass. This means that as long as suitable locations for the storage solutions can be found, the lack of available space will not be a limiting factor. Also, when planning for the energy storage portfolio, it is worth considering the impact the harsh winters might have on the different types of energy storage solutions and their performance.

Based on the research done for the aggregation of this subject, it is appropriate to point out research fields that have not been touched upon, but that were identified as relevant in order to deepen the understanding of the subject in the future. The suggestions for further research would be to assess the environmental impact and life cycle emissions of the different energy storage technologies. By mapping them, the total emissions of a renewable electricity system can be determined. This information can then further be used to decide which energy storage technologies should be preferred based on both performance and environmental impact. Further, as mentioned in the last section, the seasonal impact on the energy storage technologies should be determined. This is because the storage technologies might suffer from a severely reduced performance in non-ideal operating conditions, for instance sub-zero temperatures. An energy storage solution cannot be regarded as fitting for Finland if this is the case. As technical issues, the solution how frequency control is realised in a grid with more RES should be investigated, as well as how the increasing shares of RES with geographically scattered electricity generation will impact the current grid structure. As a last suggestion for further research, a cost analysis dictated by the national strategy could be studied. This would be an extensive study, which would take in account the political factors that have been disregarded in this thesis. As a result, the overall cheapest solution in terms of selection of RES and energy storage technology could be chosen.

Noteworthy is that even though the thesis has specifically concentrated on the electricity system of Finland, the results of this thesis can be expanded to other countries with similar electricity consumption patterns and habits. The consumption habits depend on the climate as well as the socio-economic structures and wealth of the country. Countries with similar climate and wealth as Finland are for instance the rest of the Nordic countries.

Due to the environmental awareness and tightening emission limits, the share of RES are increasing rapidly while electricity generation based on fossil fuels is being phased out. As the contribution from renewable energy generation increases, the energy storage solutions grow in importance. Still, the importance of energy storage is often overlooked by decision makers and media, resulting in poor knowledge of the limitations of RES.

Nevertheless, energy storage solutions are an indisputable part of the sustainable energy systems of the future and must not be forgotten.

Sammanfattning

I elsystem ska tillförseln av producerad el och elanvändningen alltid stämma överens. Ekvationen i elsystem blir dock svårare i och med att elanvändningen varierar beroende på tidpunkt på dygnet, det rådande klimatet samt årstiden. För att elmängden som produceras ska stämma överens med elmängden som konsumeras krävs en hög nivå av flexibilitet av elproducenterna. I vanliga fall uppnås den behövda flexibiliteten med att ha olika typers kraftverk som kompletterar varandra när det kommer till kraftverkens responstid. På så sätt kan kraftverken tillsammans tillfredsställa de krav som den varierande efterfrågan ställer på producenterna. Energisektorn har traditionellt dominerats av produktion baserat på fossila bränslen. Under de senaste årtiondena har klimat- och miljömedvetenheten dock orsakat en ökning i användningen av förnybara energikällor, och inte utan orsak. Förnybara energikällor har mindre utsläpp och därför är de att föredra framom de fossila bränslen, som fortfarande används till en stor utsträckning i elproduktion. Värt att notera är att förnybara energikällor är icke-reglerbara, vilket innebär att den förnybara elproduktionen inte kan styras i enlighet med elanvändningen och således saknas den flexibilitet som elsystem kräver. Flexibiliteten måste därmed uppnås med andra medel. En metod som har visat sig fungera i praktiken, och som denna avhandling även beaktat, är energilagring.

Energilagring innebär att då elproduktionen är högre än det momentana elbehovet, kan elen lagras för senare användning. Elektriciteten kan dock inte lagras direkt, utan den måste istället omvandlas till någon annan energiform som kan lagras. Exempel på energiformer som lämpar sig för lagring är bland annat potentiell energi, kinetisk energi samt kemisk energi. Omvandlingen från el till någon annan energiform och tillbaka till el innebär alltid förluster i och med att maskiner och apparatur har en verkningsgrad. Dessutom är energilagring ännu i dagens läge dyrt och därför är avhandlingens syfte att minimera behovet av energilagring. För övrigt är avhandlingen byggd kring elsystemet i Finland samt de möjligheter som Finland har att frångå elproduktion med fossila bränslen före år 2030. Arbetet fokuserade på två fall, ett där Finlands möjligheter att vara helt och hållet bundet till elproduktion med förnybara energikällor undersöktes och ett fall där den antagna kärnkraftskapaciteten i Olkiluoto betraktades tillsammans med de förnybara energikällorna. Inom ramen för avhandlingen antas det att Olkiluoto 3, som är över ett decennium försenat, är i drift år 2030.

För att reda ut de möjligheter som Finland skulle ha med att förlita sig på förnybar elproduktion, har i arbetet uppskattats elbehovet år 2030 samt produktionskapaciteterna för de olika förnybara energikällorna. För att approximera dessa användes befintlig forskning och de nuvarande produktionskapaciteterna som referens. Totalt sett kunde en potential som motsvarar 89,5 TWh identifieras för de förnybara energikällorna, vilket skulle innebära en ökning på 280 % jämfört med den nuvarande produktionen. Efterfrågan på el för år 2030 uppskattades dock vara 95 TWh, vilket innebär att Finland inte endast kan förlita sig på förnybar elproduktion och samtidigt vara självförsörjande redan år 2030. Enligt uträkningarna var det återstående elbehovet 6,7 TWh. Den resterande elmängden borde endera importeras från utlandet eller produceras på andra sätt. Däremot, när den antagna kärnkraftskapaciteten på 26,4 TWh från de tre reaktorerna i Olkiluoto infördes till den totala produktionskapaciteten, skulle produktionskapaciteten räcka till för att täcka den antagna konsumtionen. För det senare fallet skrevs ett beräkningsprogram, för att optimera den förmånligaste fördelningen av energiproduktionskapaciteten med hänsyn till att minimera det krav som systemet ställde på energilagringskapaciteten.

Optimeringen resulterade i en elproduktion på 96,2 TWh, med en maximal energilagringskapacitet på 1,4 TWh. Den lagrade energimängden uppnådde sitt maximum i slutet på sommaren, då elkonsumtionen och uppvärmningsbehovet varit låg under en längre tid. Elproduktionen visade sig däremot vara ganska jämnt fördelad över året och därmed påverkade inte produktionen i samma mån på mängden el som lagrats. I enlighet med optimeringen kunde vindkraft, bioenergi och vattenkraft tillsammans med kärnkraft konstateras vara en viktig del av en fossilfri elproduktion. Samtidigt kunde solenergi identifieras vara för variabelt för att lämpa sig för ett elsystem där energilagringskapaciteten är begränsad och således kunde ingen ökning för solenergi identifieras.

Potentialen att minska utsläppen då elproduktionen sköts med andra än fossila bränslen kunde även konstateras vara avsevärd. I både det fullständigt förnybara elsystemet samt det fossilfria elsystemet minskade de direkta utsläppen till noll, eftersom inga fossila bränslen användes. Däremot har även förnybara energikällor indirekta utsläpp som kan räknas i livscykelutsläpp. Livscykelutsläppen konstaterades sjukna med 11 % i elsystemet med enbart förnybar elproduktion, medan i det fossilfria elsystemet skulle utsläppen minska med 17 % från den nuvarande nivån. Elsystemet med kärnkraft och förnybara energikällor erbjöd lösningen med de minsta livscykelutsläppen. Det är värt att notera att elproduktionen var 28,7 TWh högre i det självförsörjande, fossilfria, elsystemet och därmed var utsläppsintensiteten per producerad TWh 43 % mindre än i det nuvarande elsystemet.

Eftersom ett fossilfritt elsystem saknar direkta utsläpp, är det i enlighet med Europeiska Unionens mål att vara koldioxidneutral år 2050. Ett fossilfritt elsystem är dock inte ensamt tillräckligt för att minska utsläppen med 55 % från utsläppsnivån år 1990, vilket är ett mål som den finska regeringen ställt upp. Fastän beräkningarna i avhandlingen är baserade på data från Finland, kan resultaten även tillämpas på andra länder med liknande klimat och konsumtionsvanor, exempelvis de andra nordiska länderna.

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